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The design, construction, and testing of,

is described

16. Abstract An oil skimming and separation system capable of processing 30,000 gallons per hour, and operating on the open ocean under Sea State 3 conditions, was designed, constructed, and tested.~~by the AiResearch Manufacturing Company~~. A 45 x 26-foot twin-hulled barge, which contained an entrance paddle wheel and self-adjusting skimming weirs, was built to support the skimming and separation equipment. A 500-gpm centrifuge ~~developed during the program~~ was used to reduce the oil content of the discharge water to less than 100 ppm. The recovered oil contained less than 5 percent water. The oil content of the discharge water could be reduced to less than 20 ppm by recycling it through the centrifuge a second time. The equipment was tested in natural and simulated oil slicks off the coast of Southern California under environmental conditions up to and including Sea State 3. Intentionally spilled oils of API 15, 26, and 35 gravities were recovered and separated, as were weathered oil slicks that resulted from natural under water seeps in the test area. The centrifuge was particularly useful in separating the mixtures of water and the higher API gravity oils. (Galwardi-Texas)

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OIL/WATER SEPARATION SYSTEM
WITH SEA SKIMMER

by

The Garrett Corporation
AiResearch Manufacturing Division
Los Angeles, California 90009

for the

OFFICE OF RESEARCH AND MONITORING

ENVIRONMENTAL PROTECTION AGENCY

Project #15080 DJP
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October 1970

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ABSTRACT

An oil separation and skimming barge capable of processing up to 500 gpm was designed, constructed, and operated in open ocean from Sea State 0 through 3. Test data was collected for the centrifuge on land and for the total system at Sea States 0 and 1. The major components are: (1) entrance paddle wheel, (2) louvered quiet pond, (3) self-adjusting skimming weirs, (4) storage/surge tank, (5) centrifuge plus auxiliary equipment.

The primary target performance for the centrifuge was a water discharge containing less than 100 mg/l oil and secondly an oil discharge containing less than 5 percent water starting with an influent oil emulsion of up to 40,000 mg/l. The centrifuge efficiency was dependent upon flow rate, emulsion concentration, and the gravity (°API) of the oil. For oils between 21 and 31° API, and centrifuge operating between 2750 and 3350 rpm, the primary performance was met at 100 gpm flow rate and 30,000 mg/l oil emulsion or at 500 gpm flow rate and 1000 mg/l oil emulsion. Starting with 23,000 to 48,000 mg/l oil emulsions flowing at 235 gpm it is possible to reduce the oil concentration in the discharge water to an average value of 210 mg/l. Recycling this discharge through the centrifuge reduced the oil concentration to less than 40 mg/l.

Skimmer efficiency was measured by spilling 35° API crude oil on the ocean and comparing the amount of oil recovered to the amount dumped. At 1.2 knots and Sea State 0 the skimmer displayed an efficiency of 90 percent, dropping to 75 percent at 2.3 knots and Sea State 1.

This report was submitted in fulfillment of Project No. 15080 DJP, Contract No. 14-12-524, under the sponsorship of the Water Quality Office, Environmental Protection Agency.

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SECTION I

CONCLUSIONS

The following conclusions were reached as a result of the oil skimming and separating system operation:

1. The oil skimming barge, with its paddle wheel and floating weirs, combines with the centrifuge to make a technically feasible method of removing oil from the surface of the sea.

2. The total system (skimmer and centrifuge) can recover and process up to 500 gpm (30,000 gallons/hour) of oil/water mixture.

   (a) Inlet emulsions of up to 1000 mg/l of 21° API or greater crude oil can be separated by the centrifuge operating at 3350 rpm to produce an effluent containing 100 mg/l or less of oil. Degrees API are given by the following:

   $$\text{Degrees API} = \frac{141.5}{\text{sp gr } 60^{\circ}/60^{\circ}\text{F}} - 131.5$$

   (b) Inlet emulsions of more than 1000 mg/l of oil will result in the production of effluents containing more than 100 mg/l of oil. These effluents are returned to the quiet pond in the skimmer barge for reprocessing. By recycling the effluents back through the centrifuge, oil concentrations in the produced water can be reduced to less than 100 mg/l.

3. System overall efficiency (Figure 79) for recovery of 35° API oil is 90 percent when operated at low velocity (1.2 knots) in smooth water (Sea State 0). The skimmer displayed an efficiency of 75 percent at 2.3 knots and Sea State 1. When the skimmer was operated under Sea State 3 conditions, the efficiency visually appeared to decrease although no quantitative data was taken.

4. The performance of the centrifuge when operating at constant speed is dependent upon the flow rate, emulsion concentration, specific gravity of the oil, and temperature.

   (a) Lowering the inlet rate to 100 gpm allows processing an emulsion with up to 33,000 mg/l of 21° API oil so that less than 100 mg/l remains in the discharge water.

   (b) Processing emulsions containing 10,000 mg/l of 21 to 25° API oil at 200 gpm and 2750 rpm results in discharge water with 200 mg/l of entrained oil. At the same operating conditions, but using 28 to 31° API oil, the oil concentration in the discharge water is 80 mg/l.

(c) At the same operating conditions as above with 21 to 25° API oil, raising the inlet emulsion temperature from 68 to 140°F results in a reduction of oil concentration in the effluent water from 200 mg/l to 55 mg/l.

5. The skimmer barge can be used to recover weathered oil slicks. The weathered oil is collected in the quiet pond from where it is removed by hand and stored in drums. During one 4-hour period, eighteen 55-gallon drums of tar were collected in this manner.

6. The centrifuge is capable of separating solid particles from the inlet emulsions. Starting with 9.5 mg/l of suspended oil-free solids, over 80 percent were removed from the effluent when the centrifuge was operated at 2750 rpm.

7. A standard commercially-available emulsion breaker increased the separation ability by 50 percent and its use is an economically feasible method of upgrading performance. As an example, it would cost $0.005 (1/2-cent) per bbl of emulsion to use Tretolite JN9045 ($2.51/gal.) at the tested rate of fifty parts Tretolite per million parts of emulsion.

8. The centrifuge does not attain the theoretical separation efficiency expected from Stokes' Law considerations. Oil droplets of ten microns and larger should be removed from the effluent water. However, analysis of the water samples shows that some of these droplets are not being removed.

9. A multiple-staged centrifuge would have a greater overall efficiency than the single-stage unit. When the effluent from the centrifuge was recycled, the oil concentration was further reduced.

10. This recovery/separation system can handle crude oils with gravities ranging from 21 to 35° API. The thicker materials, such as tar, will separate in the quiet pond or in the surge tank but will not progress as far as the centrifuge.

SECTION II

RECOMMENDATIONS

The following recommendations are made as a result of the tests performed.

OIL SKIMMER BARGE

A seagoing oil skimmer barge worth approximately $100,000 is now available for oil spill cleanup or, if properly maintained, for additional development of components. Since oil spills can contain a wide range of properties and can occur under a variety of conditions, it is recommended that this piece of equipment be maintained and that the modifications described below be incorporated and evaluated to obtain even better overall performance.

1. It has been found that weathered oil slicks coagulate into large masses of tar as they are drawn into the skimmer. These cannot be handled by pumping systems. A chain-belt type of conveyor could lift these masses directly from the quiet pond to a storage bin on deck. This device could also be effective in recovering oil-soaked straw or other adsorbents.

2. The three small weirs should be replaced with a single large weir for handling heavier oils. A larger pump, such as a Wellpoint 6-in. by 4-in. centrifugal pump with a vacuum unit, could be used.

3. As an alternate method to replace the weir pumps, build and test a vacuum tank system for lifting the oil/water mixture from the quiet pond. This would eliminate the weir suction pumps and the resultant emulsification. The vacuum tank would be pumped by the centrifuge inlet pump. Another alterative is to use a diaphragm pump in place of the centrifugal pump to reduce emulsification in the pumping process.

4. Modify the forward section of the quiet pond to reduce the present turbulence and the minor loss of oil through the louvers at this point. This may be done by modifying the aft end of the spillway to reduce vertical circulation, modifying the wave fences, or closing some of the forward louvers.

5. The present skimmer could be divided into sections compatible with truck, rail, or air transporation. This would make this piece of equipment available to any area of the United States within one or two days.

6. Tests reported in this study were for treatment above 68°F. More information is needed on the efficiency at lower temperatures to determine the system efficiency in colder climates.

7. Future systems should be built with a permanent power supply in the form of a diesel engine-driven hydraulic system located in the engine compartment. All other equipment would then be driven by hydraulic motors or actuators.

8. Conduct additional testing. A limited amount of testing was done at Sea States 0 and 1, and more quantitative data should be taken at these states as well as under more severe conditions.

CENTRIFUGE

1. The present centrifuge could be modified to incorporate a multiple-stage design. This would allow the unit to improve the separation of higher inlet emulsion concentrations while at the same time reducing the concentration of oil in the discharge water.

2. Incorporate the centrifuge feed pump into the design of the inlet section of the centrifuge. The centrifuge discharge section would have to be designed to be compatible with the inlet section characteristics. This would eliminate one of the undesirable emulsifying components.

SECTION III

INTRODUCTION

Spills of crude oil, refined products, vegetable and fish oils on marine and inland waters occur from many sources and pose a constant threat to the beneficial use of these waters and the adjacent shoreline. Sources of oil spills include vessels, industrial establishments, pipelines, terminals, and offshore drilling operations. Usually in the recovery of those spills, large quantities of water are also picked up with the oil. In order to reduce the amount of liquid to be transported from the spill site to the eventual disposal area, it is desirable to remove as much of this excess water as possible at the recovery site.

In the past, this separation step had not been done or it had been accomplished by allowing the recovered product to settle in large tanks prior to drawing off the excess water. Finely divided emulsions can require a prohibitive settling time.

In the program described in this report, an investigation was made to evaluate the feasibility of using a centrifuge to speed the removal of oil from the recovered oil/water mixture. From previous testing on a prototype 5-gpm centrifuge, it was expected that oil/water mixtures containing one percent oil (10,000 mg/l) could be separated so that less than 0.01 percent (100 mg/l) oil remained in the water. The centrifuge is not designed to separate mixtures in which the oil has weathered into tar. Based on these preliminary tests, a program was initiated by the EPA/Office of Research and Monitoring for AiResearch to design, build and test a centrifuge of 500 gpm capacity to separate oil/water mixtures collected during recovery of oil spills from the sea.

The program was later modified to include the design, construction, and testing of an ocean-going oil skimmer capable of removing 500 gpm of oil/water mixtures from the surface of the ocean. This equipment was used to test the system under actual operating conditions and environment.

The separator is a horizontal centrifuge with axial inlet and discharge ports that allows a throughput rate of 500 gpm with a power consumption of 60 horsepower. A thin annular channel at the periphery of the centrifuge resulted in a small displacement distance for the oil droplets migrating under the influence of the high centrifugal forces.

The oil skimmer was designed as an independent seaworthy craft capable of supporting the required skimming equipment, the centrifuge, and the men required to operate the system. The skimmer also contained an entrance paddle wheel, self-adjusting weirs, storage/surge tanks, and a large quiet pond with a louvered bottom that carried skimmed water and oil along within the hull of the skimmer. This allowed preliminary settling; the resultant thickened oil film was then skimmed by means of a weir system. Before being returned to the ocean, the excess water skimmed with the oil was passed through the centrifuge.

A summary of the program is shown in Table 1. Approximately 48 percent of the effort was expended in the fabrication of the centrifuge and 22 percent in the construction of the skimmer barge. As originally planned, testing was limited to five days at sea. However, 20 additional at-sea days were accumulated with the equipment under a concurrent contract with the American Petroleum Institute.

TABLE I
PROGRAM SUMMARY

TASK	1969												1970												PERCENT OF EFFORT
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	
TRADE-OFF STUDIES				■	■																				2
CENTRIFUGE LAYOUT DRAWING					■	■																			3
CENTRIFUGE DETAIL DRAWINGS							■	■	■																5
CENTRIFUGE FAB. AND ASSEMBLY										■	■	■	■												48
CENTRIFUGE TESTS														■	■	■	■								7
MODEL TESTS											■	■													1
SKIMMER DESIGN										■	■	■													2
SKIMMER FABRICATION															■	■									22
SYSTEM ASSEMBLY																	■								2
SYSTEM TEST (5 DAYS OF AT-SEA TESTS)																		■							3
SYSTEM MADE AVAILABLE TO THE AMERICAN PETROLEUM INSTITUTE FOR ADDITIONAL TESTING WITH SKIMMING BOOMS AND OIL CONTAINER																			■	■					0
FINAL REPORT																						■	■	■	3
TOTAL																									100

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SECTION IV

OBJECTIVE

The objective of the oil spill recovery program was to demonstrate recovery and separation of an oil slick from the surface of the ocean under conditions up to and including Sea State 3 (Table 2). The program consisted of two tasks:

1. Design, build, and test a prototype model of an oil/water centrifuge with these objectives:

    (a) Capable of separating a wide range of mixtures and emulsions of crude oils and water.

    (b) Capable of separating oil/water mixtures at a rate of up to 500 gpm.

    (c) Capable of minimizing level of oil contamination in the effluent water. The target performance was a minimum concentration of 100 mg/l of oil in the water effluent and 5 percent water in the oil phase.

    (d) Capable of minimizing the water content in the recovered oil to the extent that it does not compromise (c) above.

    (e) Capable of being readily transported.

2. Design, build, and test a seaworthy skimmer to be used with the centrifuge to recover oil slicks from harbors and open seas, the skimmer to incorporate a paddle wheel, skimming well, self-adjusting floating weirs for skimming the oil, and a surge tank to ensure a submerged inlet to the centrifuge. The objectives for the skimmer are:

    (a) Capable of recovering thin films, light crude oil, refined products, and/or heavy films of lower gravity and/or weathered crudes and crude emulsions.

    (b) Capable of functioning in a quiet harbor, around piers, docks, vessels, with trash and debris present, and/or in open waters, including the high seas, under Sea State conditions 0, 1, 2, and 3.

    (c) Capable of sweeping up to 30 acres/hr using auxiliary side attachments (booms).

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TABLE 2

SEA STATE TABLE*

Sea State	Sea Description	Wind Description	Wind Velocity, knot	Average Wave Height ft	Significant Wave Height, ft	Approximate Period Range, sec
0	Ripples	Light airs	2	0.05	0.08	up to 1.2 sec
1	Small wavelets, still short	Light breeze	5	0.18	0.29	0.4 to 2.8
	Large wavelets, crests begin to break	Gentle breeze	8.5	0.6	1.0	0.8 to 5.0
2			10	0.88	1.4	1.0 to 6.0
	Small waves, becoming larger	Moderate breeze	12	1.4	2.2	1.0 to 7.0
3			13.5	1.8	2.9	1.4 to 7.6
			14	2.0	3.3	1.4 to 7.8
			16	2.9	4.6	2.0 to 8.8
4	Moderate waves, taking a more pronounced long form	Fresh breeze	18	3.8	6.1	2.5 to 10.0
			19	4.3	6.9	2.8 to 10.6
5			20	5.0	8.0	3.0 to 11.1
	Large waves begin to form	Strong breeze	22	6.4	10	3.4 to 12.2
			24	7.9	12	3.7 to 13.5
6			24.5	8.2	13	3.8 to 13.6
			26	9.6	15	4.0 to 14.5
	Sea heaps up and white foam from breaking waves begins to form	Moderate gale	28	11	18	4.5 to 15.5
7			30	14	22	4.7 to 16.7
			30.5	14	23	4.8 to 17.0
			32	16	26	5.0 to 17.5
	Moderately high waves of greater length	Fresh gale	34	19	30	5.5 to 18.5
			36	21	35	5.8 to 19.7
			37	23	37	6 to 20.5
8			38	25	40	6.2 to 20.8
			40	28	45	6.5 to 21.7
	High waves; sea begins to roll; visibility affected	Strong gale	42	31	50	7 to 23
			44	36	58	7 to 24.2
9			46	40	64	7 to 25
	Very high waves with long overhanging crests	Whole gale	48	44	71	7.5 to 26
			50	49	78	7.5 to 27
			51.5	52	83	8 to 28.2
			52	54	87	8 to 28.5
			54	59	95	8 to 29.5
	Exceptionally high waves; Visibility affected	Storm	56	64	103	8.5 to 31
			59.5	73	116	10 to 32
	Air filled with foam and spray	Hurricane	> 64	> 80	> 128	10 to 35

S-60636

*From Handbook of Ocean and Underwater Engineering, John J. Meyers. ed., McGraw-Hill, New York, 1969.

SECTION V

DESCRIPTION OF SYSTEM

The system shown schematically in Figure 1 and pictorially in Figure 2 consists of the following two major components:

1. Skimmer Barge--This vessel contains weirs, pumps, and the necessary oil/water processing equipment to recover oil from the ocean surface. Initial separation of the oil and water is accomplished by draining excess water out through the louvered bottom of the quiet pond. A second separation step occurs as the weirs skim the oil-rich surface from the quiet pond. A third separation is done in the surge tank where the pumped oil floats to the surface. The remaining water in the surge tank is passed through the centrifuge to remove the smaller oil droplets still remaining in suspension. The design and development of the barge is described in Section VI.

2. 500-gpm Centrifuge--The separation of the subsurface oil/water emulsion from the recovered oil is accomplished by means of an oil/water centrifuge. The design objective was to produce a centrifuge capable of discharging oil with less than 5 percent water and water with less than 100 mg/l of oil. The centrifuge is shown in Figure 3 and the design and development is described in Section VII.

For the sea tests the centrifuge was mounted on the skimmer barge and became an integral part of the overall recovery/separation system. Although this equipment performs the critical function of recovery and separation, certain additional equipment is required for a complete ocean oil spill recovery system, namely, containment booms and an oil storage tank. These were supplied through a concurrent contract with the American Petroleum Institute.

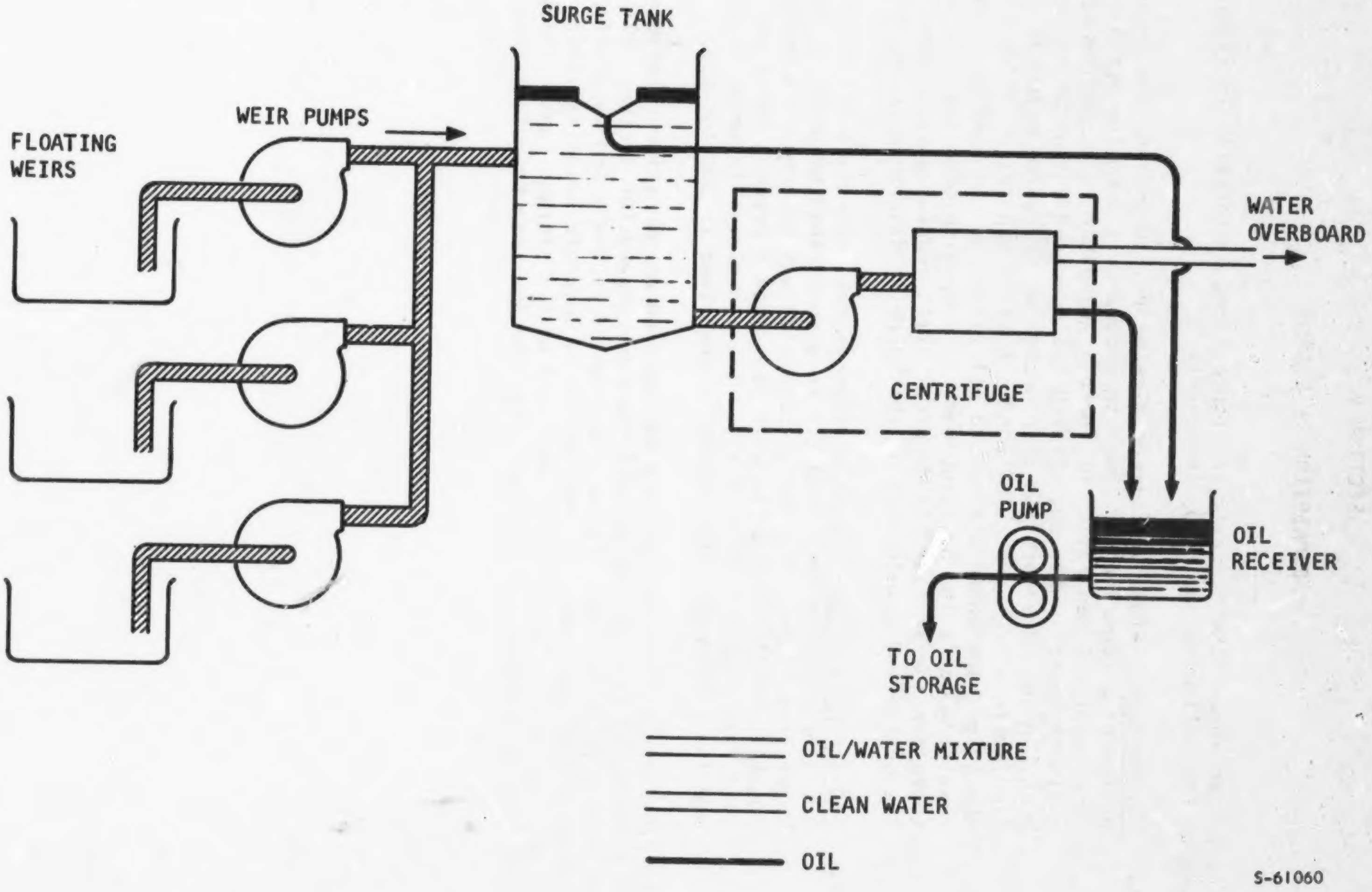

Figure 1. Simplified Oil Skimmer Barge Piping Schematic

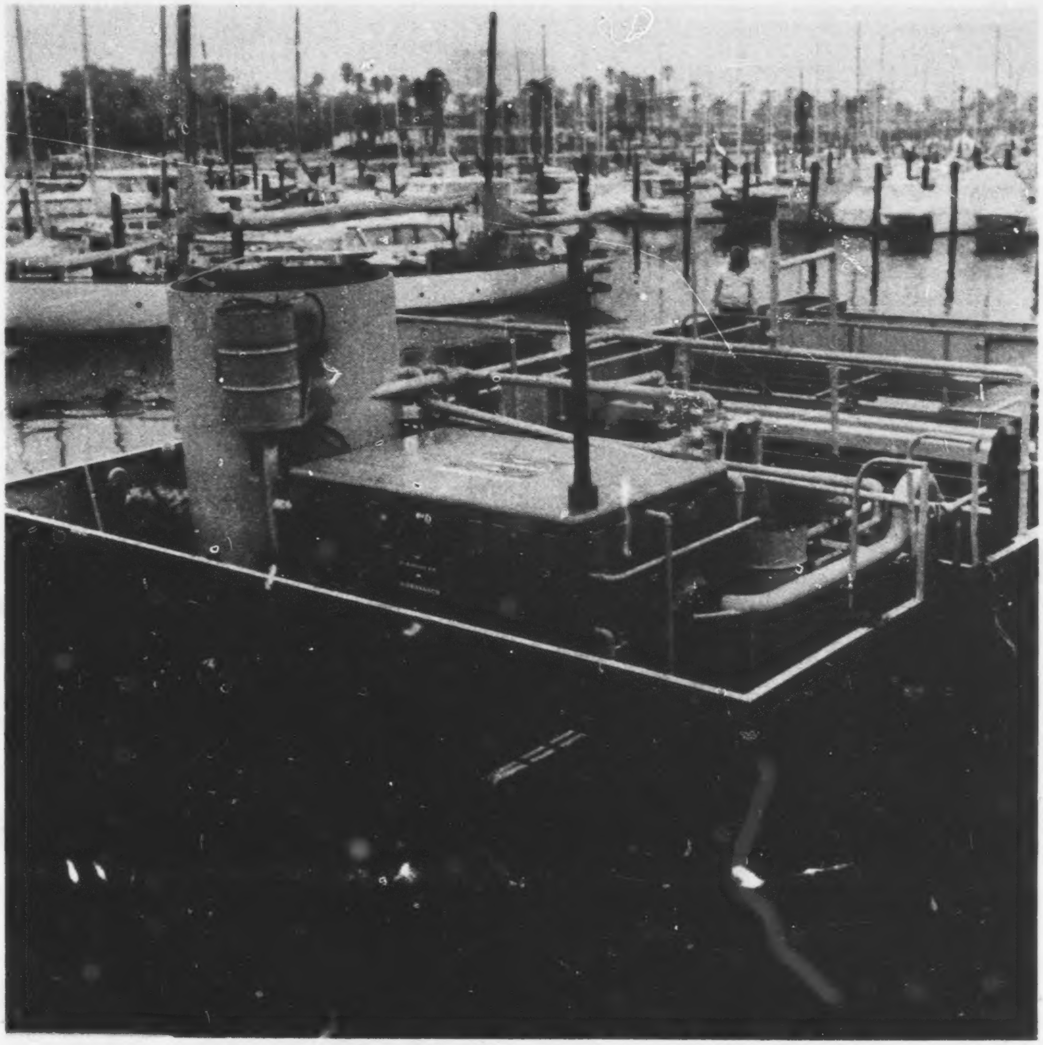

Figure 2. Oil/Water Separator Installation on Skimmer

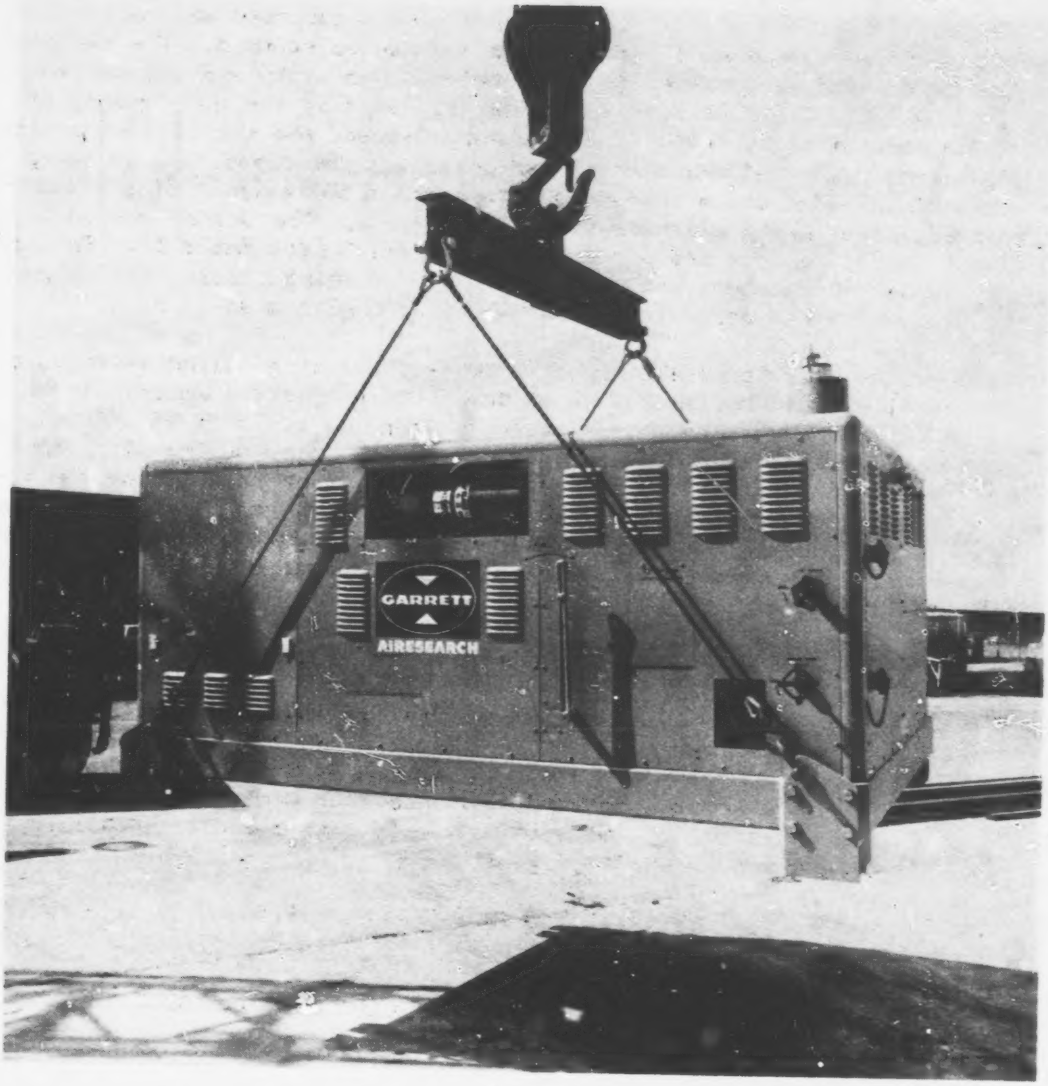

Figure 3. Oil/Water Separator

SECTION VI

SKIMMER BARGE

INTRODUCTION

The major function of the skimmer barge was to suppress wave action and obtain a quiet pond from which the surface oil may be skimmed. The overall size was determined by considering the potential sea state and the surface area to be swept. These in turn determined the size of the quiet pond, the rate of processing of skimmed fluid, the barge speed, and the size of processing equipment. The goal for the skimmer barge was the capability to sweep by the booms 30 acres of ocean surface and to process 500 gal/min of surface fluid. Barge speed versus sweep width is shown in Figure 4. The vessel was to be capable of operating from Sea State 0 to Sea State 3 (see Table 2). From the foregoing problem statement and consultations with shipbuilders, the optimum size of the vessel was determined to be 45 ft long with a 26-ft beam.

In order to operate effectively the self-adjusting floating weirs used to skim the oil had to be located in an environment of still water. If the skimmer barge is moving through the water to increase its area of operation, the water in the immediate vicinity of the weir has to be moving with the barge to obtain a zero relative current. This was to be obtained by the installation of suitable baffles or other devices between the two hulls of the barge. Since the cost of building, evaluating, and changing full-scale components of the skimmer was prohibitive, a one-twelth-scale model was built for evaluation purposes.

MODEL DESIGN, CONSTRUCTION, AND TEST RESULTS

A one-twelth-scale model of the oil skimmer barge was built and tested with these initial objectives:

1. To determine whether a simple U-shaped hull with two side pontoons and a closure across the stern would be sufficient to stop relative water motion on top of the quiet pond.

2. To determine if the addition of a forward spillway, or weir, would suffice to stop relative water motion on the top of the quiet pond.

3. To determine if a louvered bottom between the hulls would suffice to stop relative water motion on top of the quiet pond.

4. To determine if a combination of all of these devices is necessary.

After these questions were resolved, the model was further developed to evaluate the effect of the paddle wheel and other wave-damping devices. Eventually a self-adjusting floating weir and pumping equipment also were installed

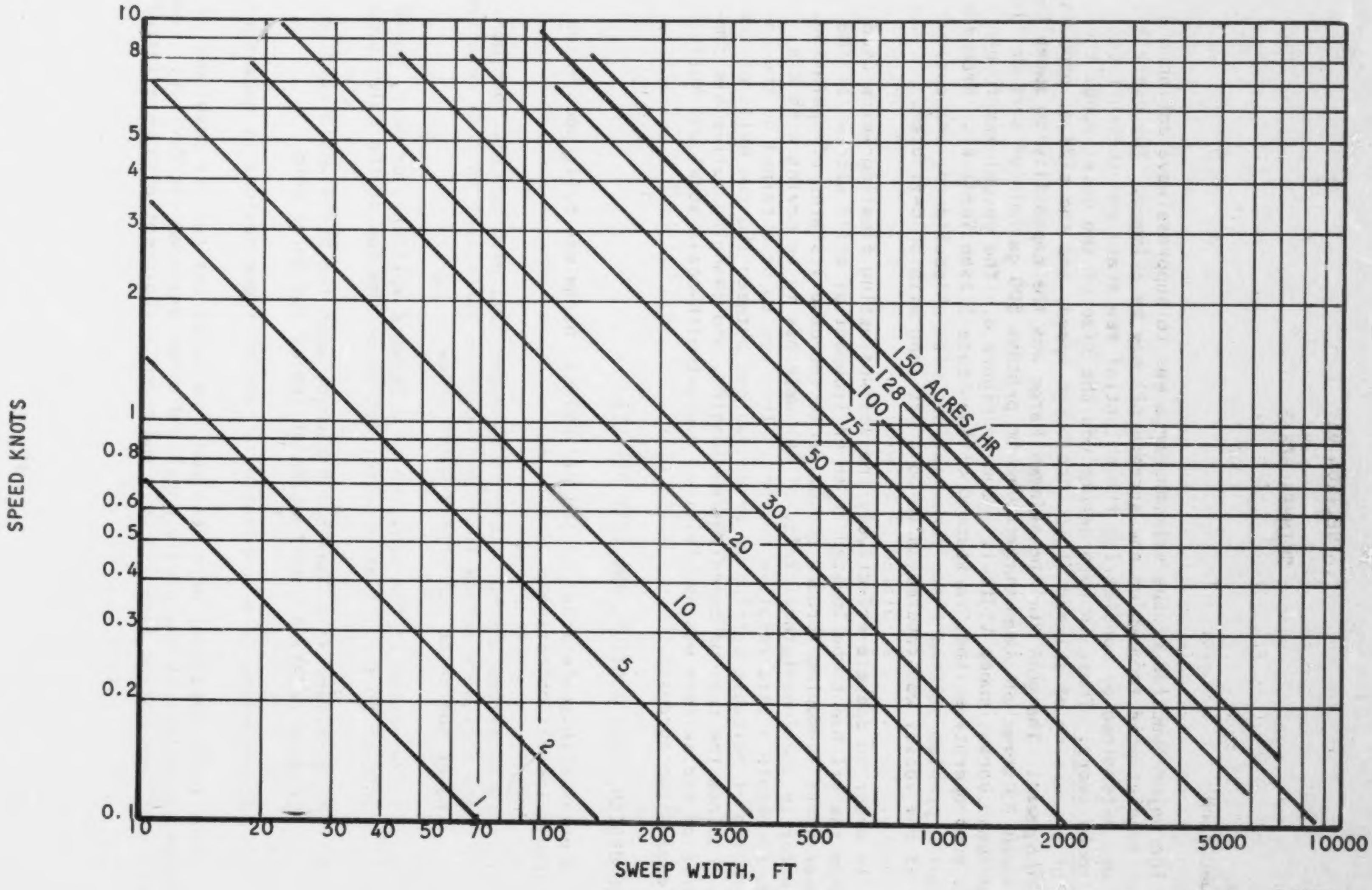

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Figure 4. Areas Swept for Various Speeds and Sweep Widths

The model was constructed with removable components so that these components could be tested in various configurations. Test data consisted primarily of visual observations and an 8-mm color movie record of the tests. These were taken at 64 frames/sec, which produced a full-scale effect when viewed at 16 frames/sec. Details of important phenomena were also examined frame by frame on a viewer. Small wooden floats were attached to the bridge structure across the quiet pond by means of strings. These, along with powder floating on the water surface, assisted in determining the direction and approximate velocity of the water currents.

First Model Version

The model was built of 1/4-in. plywood to the scale of one inch to a foot. (All dimensions in this section are model dimensions. For full-scale dimensions change inches to feet.) The model was divided into several watertight compartments so that various conditions of ballast could be simulated.

As originally constructed, the model consisted of the engine compartment and the twin hulls. A simulated 6-in.-wide paddle drive bridge was installed immediately behind the 8-in.-diameter paddle wheel. The paddle drive mechanism shown in Figure 5 was mounted upon this bridge. Also constructed were the louvered bottom and the forward bottom sections. These parts were removable to permit evaluation of their effect. An 8-bladed, 8-in.-diameter paddle wheel was used.

These tests were conducted on November 24, 1969 by manually towing the model alongside a long dock at Alamitos Bay. The primary purpose of this test series was to determine the necessity of the louvered bottom and forward spillway. The model was towed at various depths and speeds to simulate a wide set of conditions.

The fluid forces that are relevant in ship model testing are the inertial and gravitational forces. The relationship between these must be identical for both the full scale and model unit:

$$F_I = Ma = \rho L^3 \frac{V^2}{L} = \rho V^2 L^2$$

$$F_G = Mg = \rho L^3 g$$

$$\left(\frac{F_I}{F_G}\right)_P = \left(\frac{F_I}{F_G}\right)_M = \left(\frac{V^2}{Lg}\right)_P = \left(\frac{V^2}{Lg}\right)_M$$

where F_I = inertial force, lb

M = Mass of object, lb-sec^2/ft

a = Acceleration, ft/sec^2

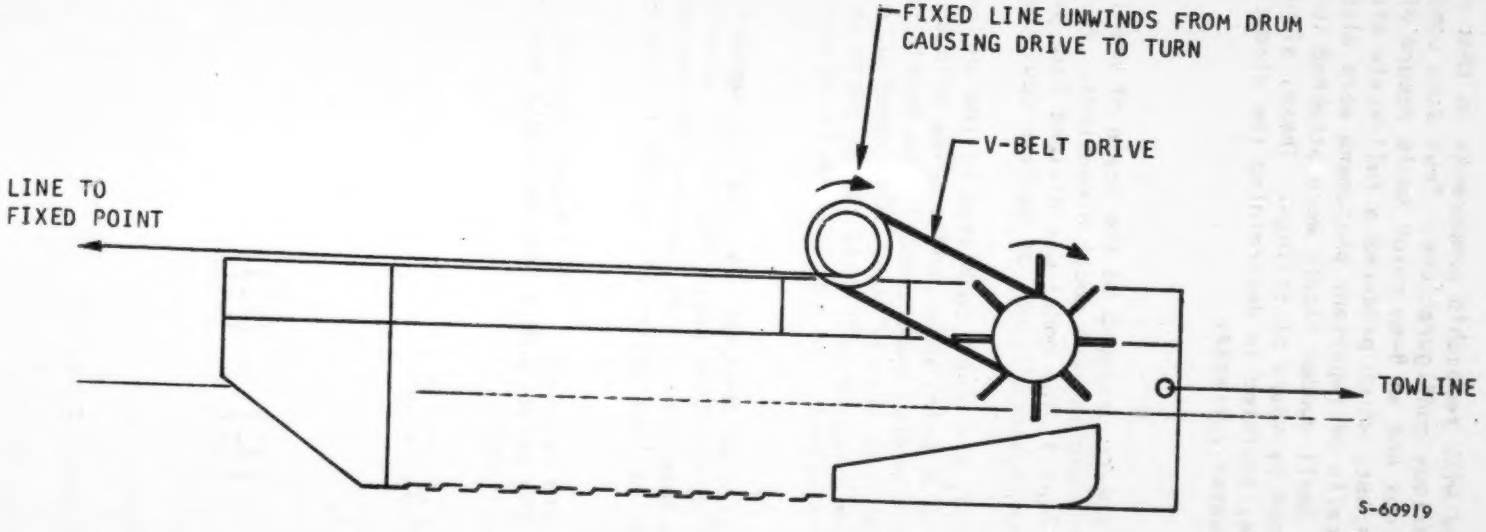


Figure 5. Paddle Drive Mechanism

ρ = Fluid density, lb-sec^2/ft

L = Length, ft

V = Velocity, ft/sec

F_G = Gravity force

g = gravitational acceleration, 32.2 ft/sec^2

Subscript

P = Full-scale prototype

M = Model

therefore

$$\frac{V_P}{V_M} = \frac{\left(\sqrt{Lg}\right)_P}{\left(\sqrt{Lg}\right)_M} = \frac{\sqrt{L_P}\ \sqrt{g}}{\sqrt{L_M}\ \sqrt{g}} = \frac{\sqrt{L_P}}{\sqrt{L_M}}$$

Using this relationship, the equivalent speed for a one-twelth-scale model is shown in Figure 6.

Without a bottom in the barge, the water through which the model was being towed did not deflect until just in front of the pond aft bulkhead, as shown in Figure 7. This was an unsatisfactory condition because the floating weirs were being pushed through the water at essentially boat speed. This upset the operation of the weir.

Adding the louvered bottom tended to slow the water at the forward end of the quiet pond, (Figure 8); however, there was still considerable velocity at the weir location.

Addition of the spillway reduced the amount of water that entered the quiet pond; the flow pattern is shown in Figure 9. Floats, tied to the paddle drive bridge by strings, floated idly in the region of the weirs, showing ideal current conditions in the quiet pond.

When the louvered bottom was removed but the spillway retained, a reverse-flow eddy was created, as shown in Figure 10, which carried the indicating floats forward over the spillway. This condition would cause the surface oil to move away from the weir inlet.

Evaluation of the paddle wheel was unsuccessful because the drive mechanism was too elastic to drive the paddle at a constant speed. Also, there were no waves at this test site to test the ability of the paddle in attenuating incoming waves.

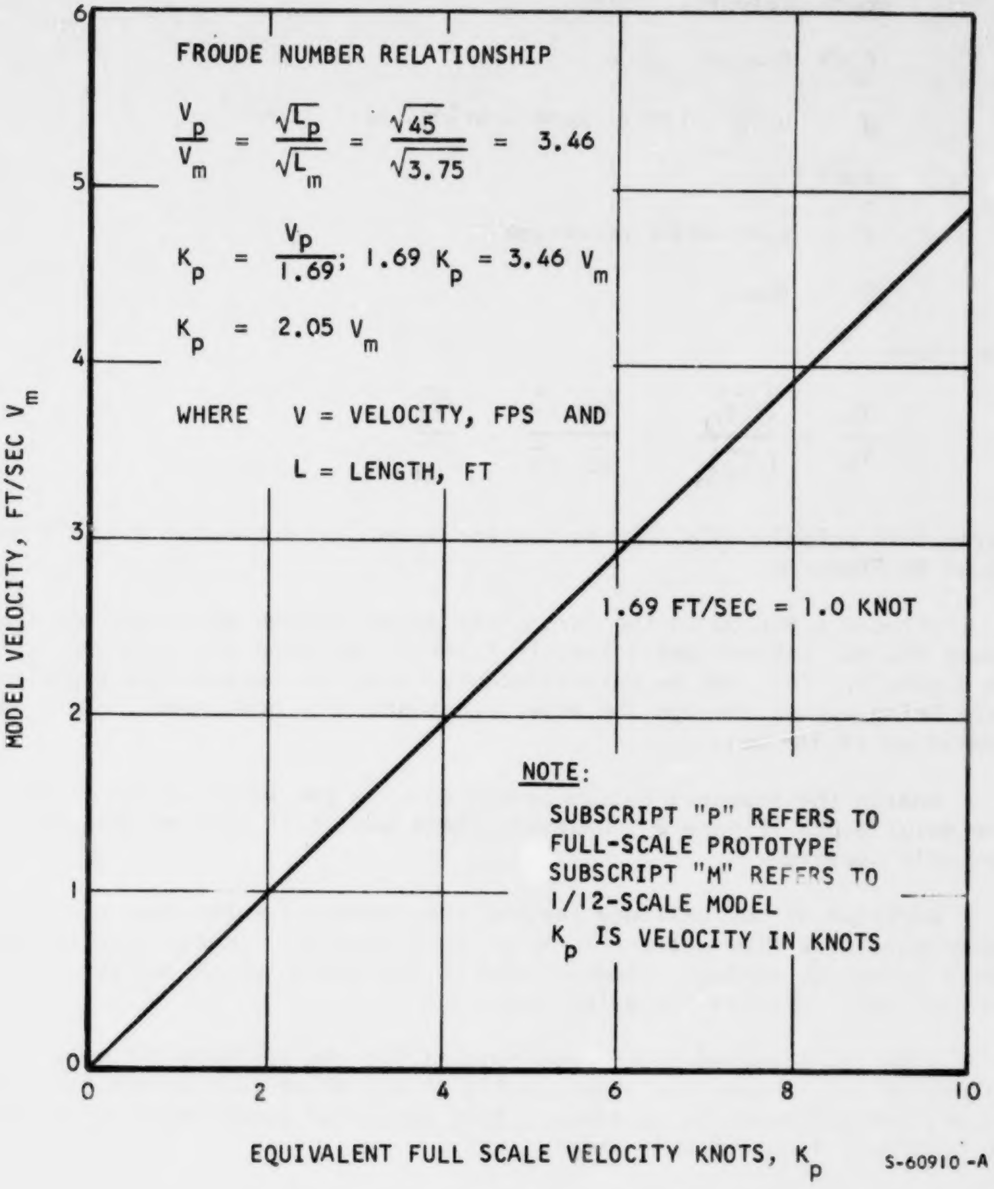
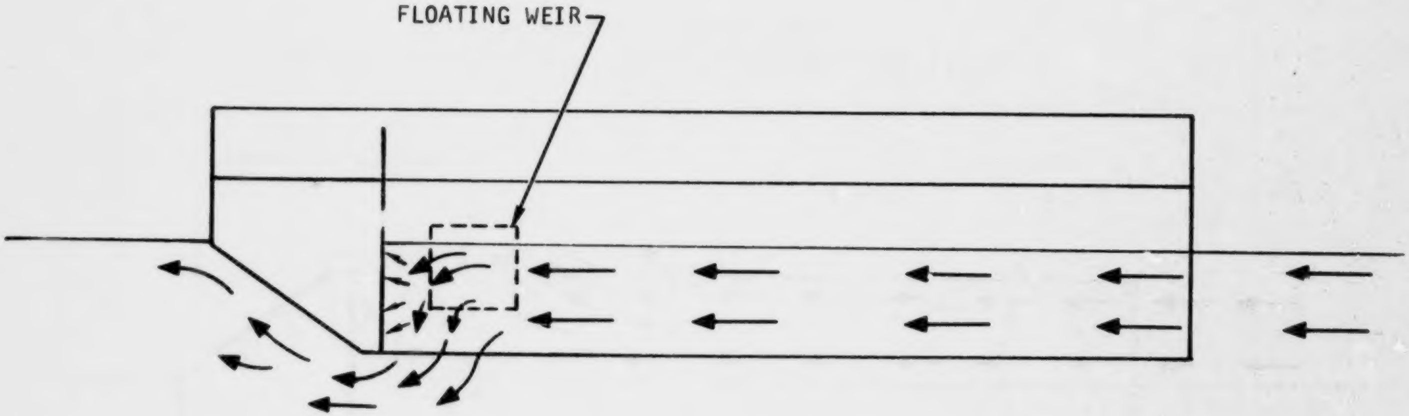


Figure 6. Relationship of Model Speed to Full-Scale Speed



NOTE: LENGTH OF ARROW INDICATES APPROXIMATE VELOCITY, RELATIVE TO CATAMARAN, OF WATER FLOW.

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Figure 7. Flow of Water through the Catamaran if no Bottom is Used

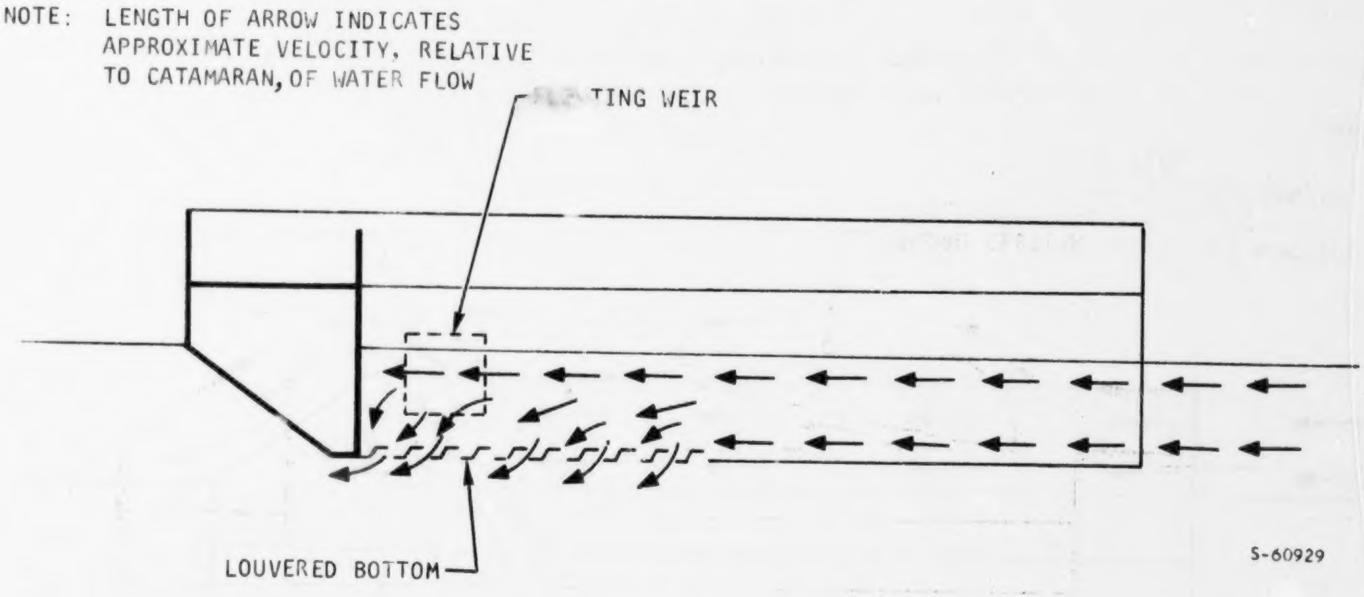
NOTE: LENGTH OF ARROW INDICATES APPROXIMATE VELOCITY, RELATIVE TO CATAMARAN, OF WATER FLOW
FLOATING WEIR
LOUVERED BOTTOM
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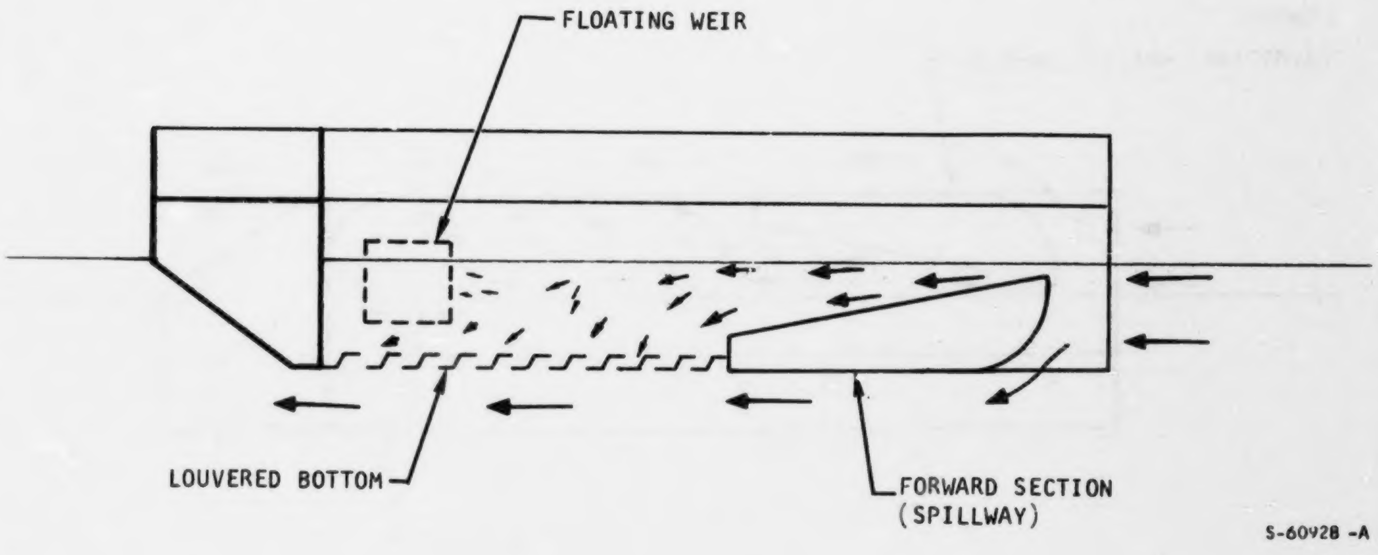
Figure 8. Flow of Water through the Catamaran if the Louvered Bottom is Installed



NOTE: LENGTH OF ARROW INDICATES APPROXIMATE VELOCITY, RELATIVE TO CATAMARAN, OF WATER FLOW

Figure 9. Water Flow through the Catamaran when a Louvered Bottom and a Forward Section is used

NOTE: LENGTH OF ARROW INDICATES
APPROXIMATE VELOCITY, RELATIVE
TO CATAMARAN, OF WATER FLOW.

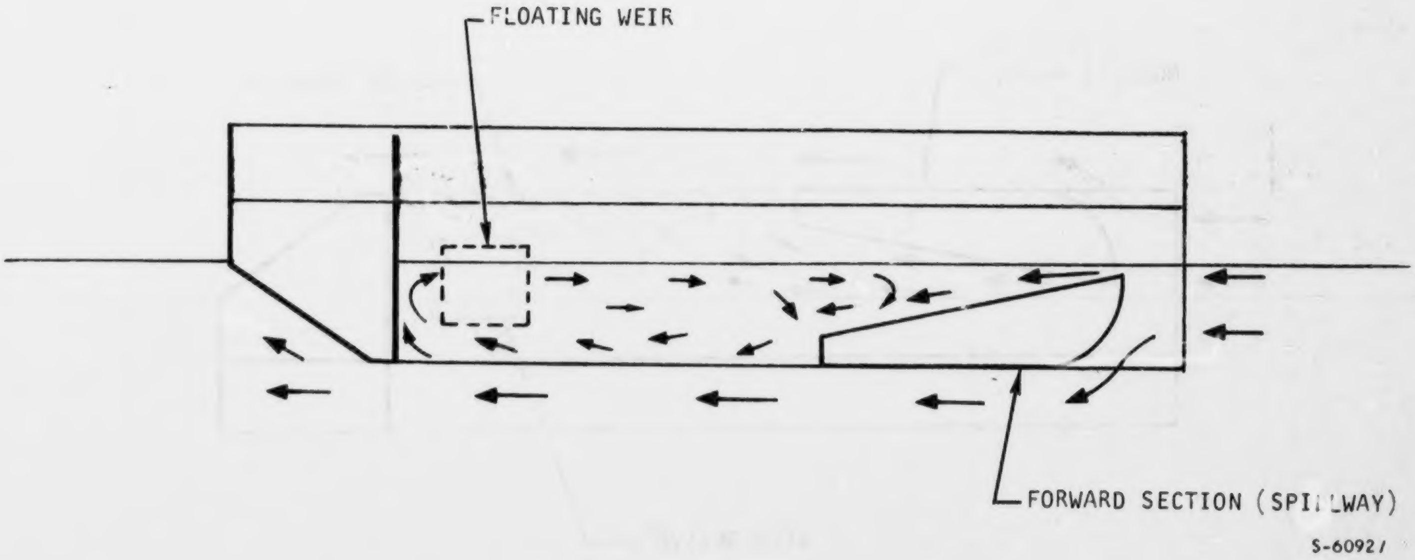


Figure 10. Water Flow through the Catamaran when the Forward Section is Used without the Louvered Bottom Section

The model was also towed backwards at simulated speeds up to 8.2 knots in the unballasted (lightest) configuration. It towed very well, although observation of the floats indicated some eddy current in the quiet pond.

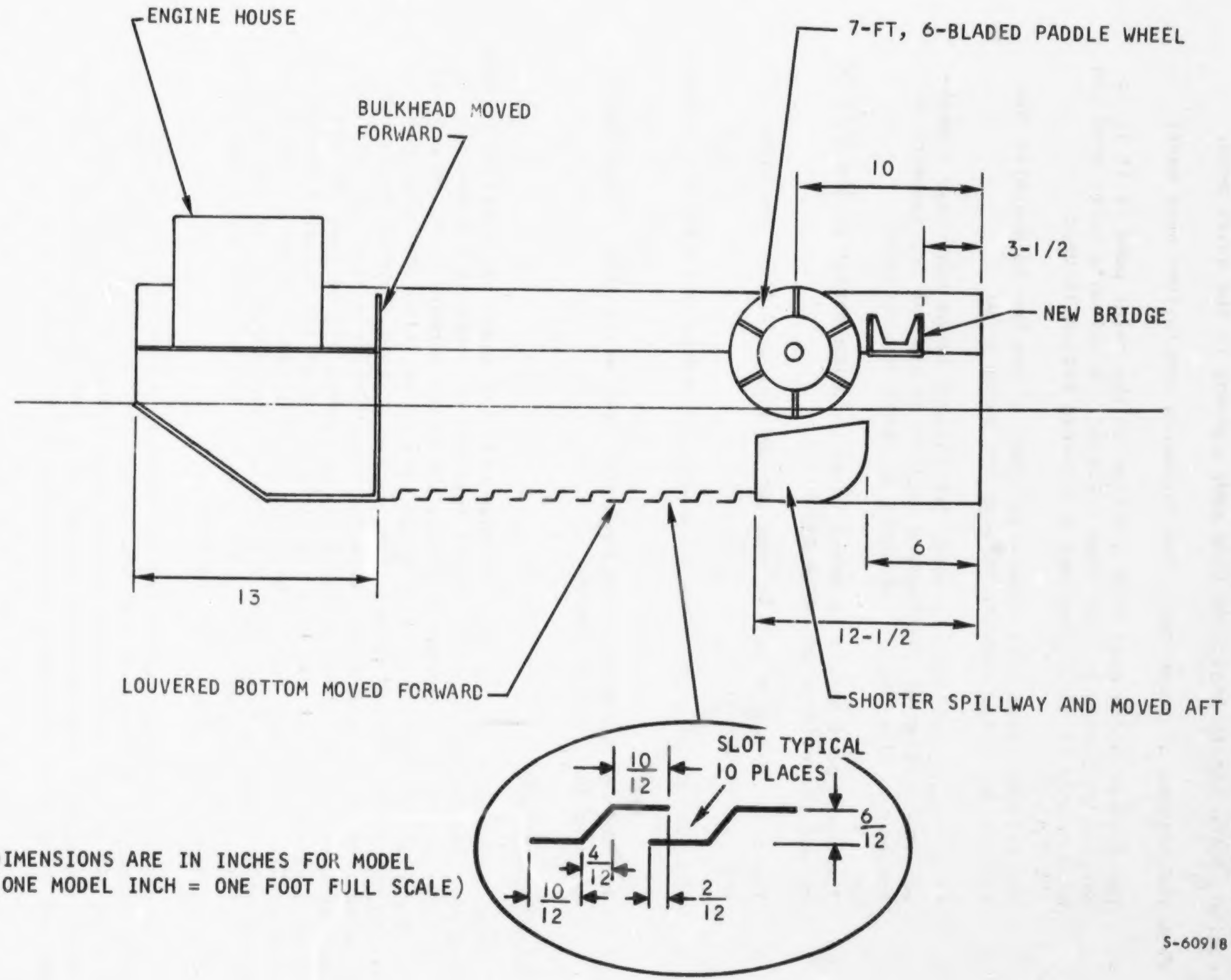
From the results of these tests the following conclusions were made:

1. The skimmer barge must have a bottom to the quiet pond if it is to operate at speeds greater than 1/2-knot. A suitable quiet pond can be produced if a spillway and a louvered bottom is used.
2. The skimmer barge must have a spillway at the bow to minimize the quantity of water flowing through the quiet pond.
3. If a sloping spillway is used, the skimmer barge must have a near-vertical bottom at the forward section to prevent the tendency of the bow to rise out of the water as speed is increased.
4. The quiet pond should be moved forward to the center of the hull to reduce the effects of barge pitching.
5. The free surface effect of the bottom area will help the barge lift over large waves.
6. The long sloping spillway was a wave generator and should be greatly shortened.
7. The skimmer barge will tow backwards very well; this method should be used for to-site towing.

Second Model Version

After completion of the tests in November, the model was modified to make improvements and incorporate additional features as shown in Figures 11, 12, and 13. The engine room forward bulkhead was moved forward 6 in. to provide for a larger engine room, more deck space, and to position the quiet pond closer to the center of the barge. The 19-1/2-in.-long louvered bottom was also moved forward an equivalent distance. The 10-1/2-in. spillway with the 10-deg diffuser was cut short to 6-1/2 in. and moved aft so that the aft vertical bulkhead was in line with the forward end of the louvered bottom. A six-bladed 7-in.-diameter paddle wheel was substituted in place of the 8-in.-diameter eight-bladed paddle wheel and its axis was moved aft to the 10-in. station. Also, the original paddle drive bridge was removed and a new one, forward of the paddle wheel, was installed.

The paddle drive was mechanized by means of a 12-volt electric motor driving through a gearbox and a 65-in. V-belt to the paddle wheel. The motor drive and its 12-volt motorcycle battery were housed in the cabin that was added to the model. Paddle speed changes were made by changing drive pulley sizes and a variable resistance in the motor drive circuit.



NOTE: DIMENSIONS ARE IN INCHES FOR MODEL
(ONE MODEL INCH = ONE FOOT FULL SCALE)

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Figure 11. Barge Model as Modified for January 6 Tests

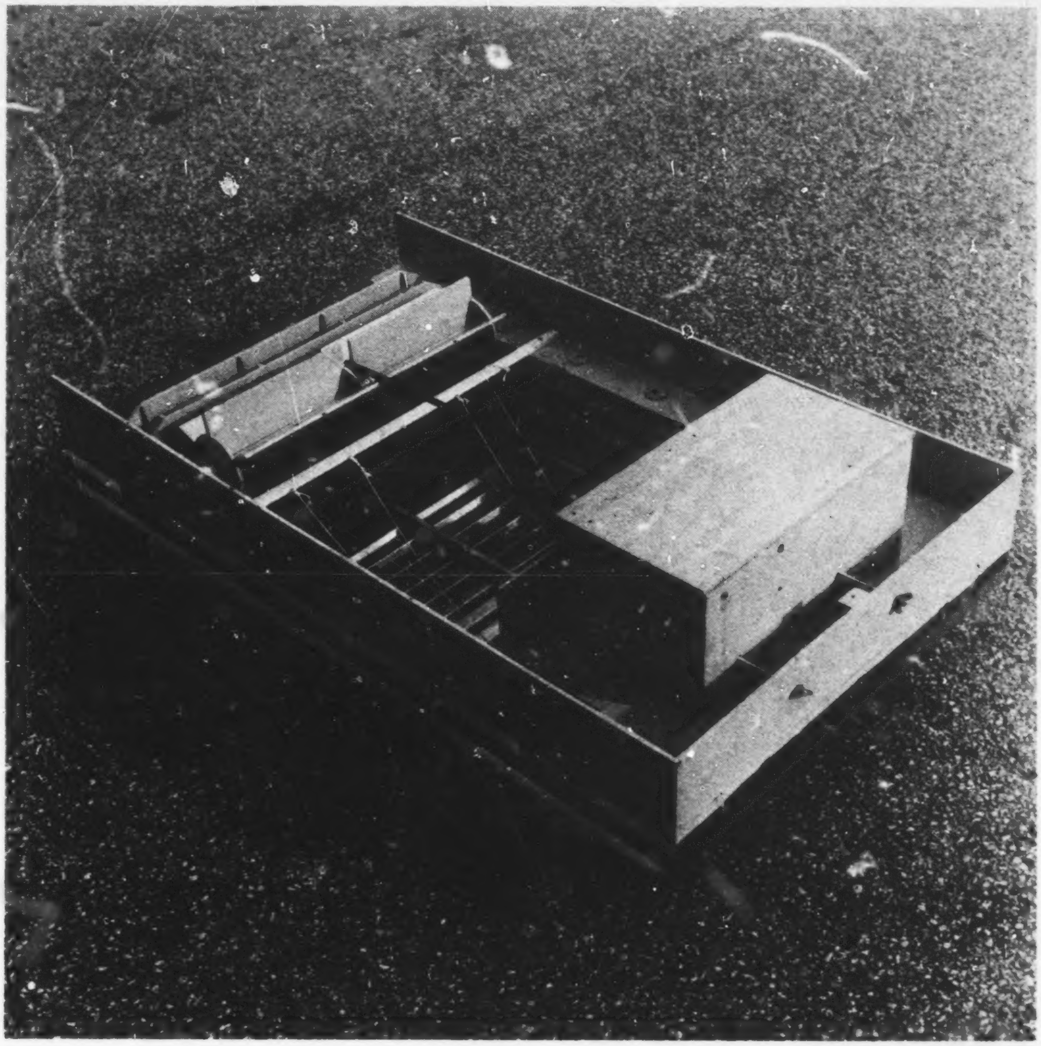


Figure 12. Oil Skimmer Barge 1/12th-Scale Model with Paddle Wheel

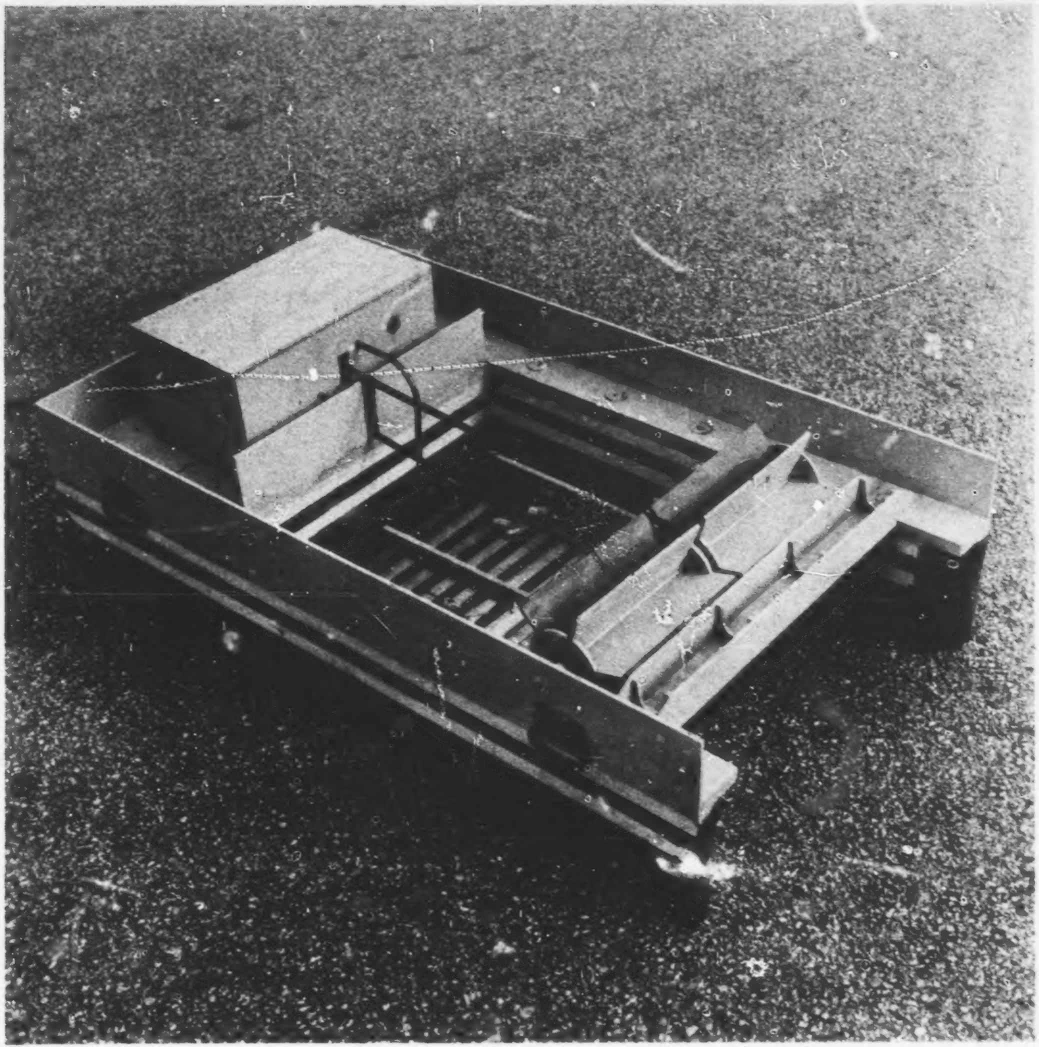


Figure 13. Oil Skimmer Barge 1/12th-Scale Model with Paddle Wheel

After modifications, the model was towed in the open waters of Newport Harbor to evaluate the paddle wheel as a wave attenuator and a surface oil mover. The tests were only partially successful because the tow boat could not be operated at a speed slow enough for good model testing. The ability of the paddle to attenuate waves was not established, but it was a definite help in bringing the oil surface within the catamaran at the lower towing speeds.

The configuration was then changed to that shown in Figures 14 and 15, and the model was tested in rougher water than previously observed. The use of a sloping surface instead of the paddle wheel appeared to be a better method of attenuating the wave action. It did not appear to cause as much disturbance in the quiet pond.

Later the same day the model was taken to Alamitos Bay and towed along the dock in the same manner the tests of November 24th were run. Perlite floating on the water was used as an indicator during these tests. Visual observations indicated that the paddle wheel aided in collecting the Perlite into the quiet well during operation in quiet water.

The following conclusions were derived from these tests:

(a) The action of the paddle wheel generated a choppy wave condition in quiet pond.

(b) The paddle wheel, if driven at the proper speed, is an effective device for moving the oil surface towards the weir inlet. The speed must be adjusted so that the paddle blade does not cause a bow wave nor unduly disturb the water surface. This represents a peripheral speed approximately equal to the forward motion of the skimmer. At skimmer speeds of less than one knot, the paddle can be operated at a peripheral speed of approximately one knot without unduly disturbing the water surface.

(c) The sloping-surface convergent passage of the spillway is an effective wave attenuator.

Third Model Version

A floating weir as shown in Figure 16 was added to the skimmer model. An automotive electric fuel pump was used to pump the oil and water from the weir to an adjacent receiver. This pump, shown in Figure 17, was also powered by the 12-volt motorcycle battery and had a pumping capacity of 0.5 gpm. In order to reduce the sloshing in the quiet pond, two vertical gratings, called wave fences, were installed as shown in Figure 18.

The model as shown in Figures 19 through 21 was tested by towing it behind a small skiff in Marina del Rey. The original intent of the test was to recover oil from the quiet pond by means of the floating weir while the model was being towed through a simulated sea condition. The pump, however, failed to work properly so this function was tested during only a few intermittent periods of operation. These results were sufficient to indicate feasibility of the operation.

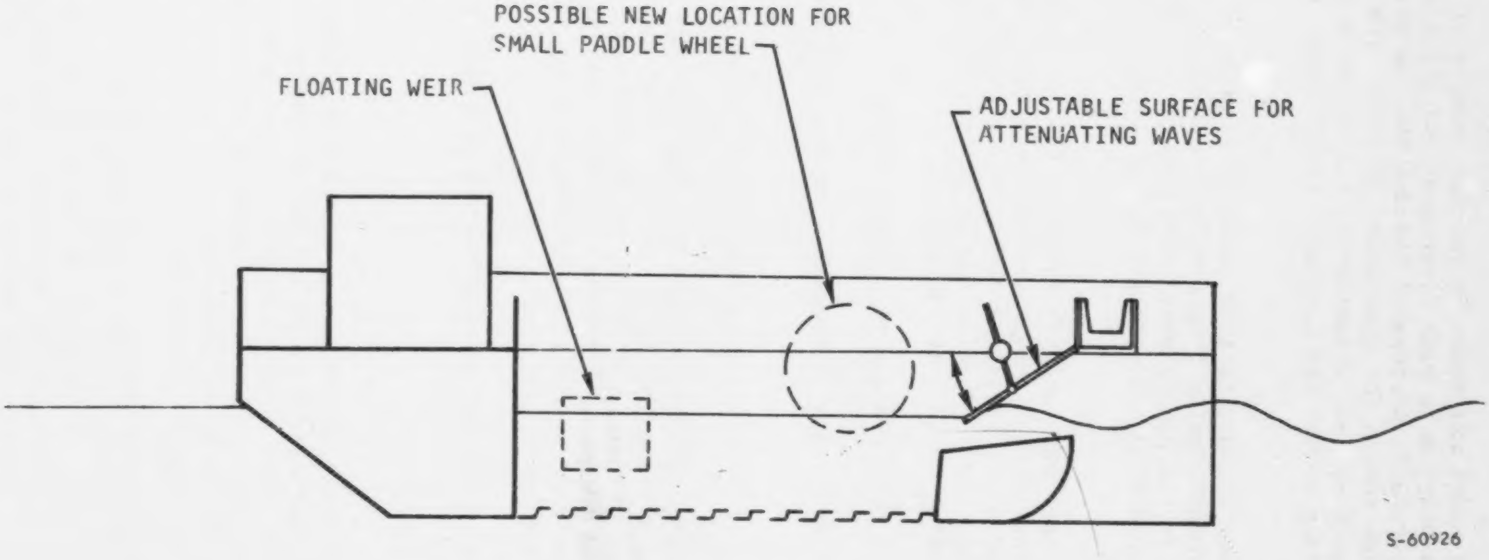


Figure 14. Configuration of Model for Converging Passage Type Wave Attenuator (January 6 Tests)

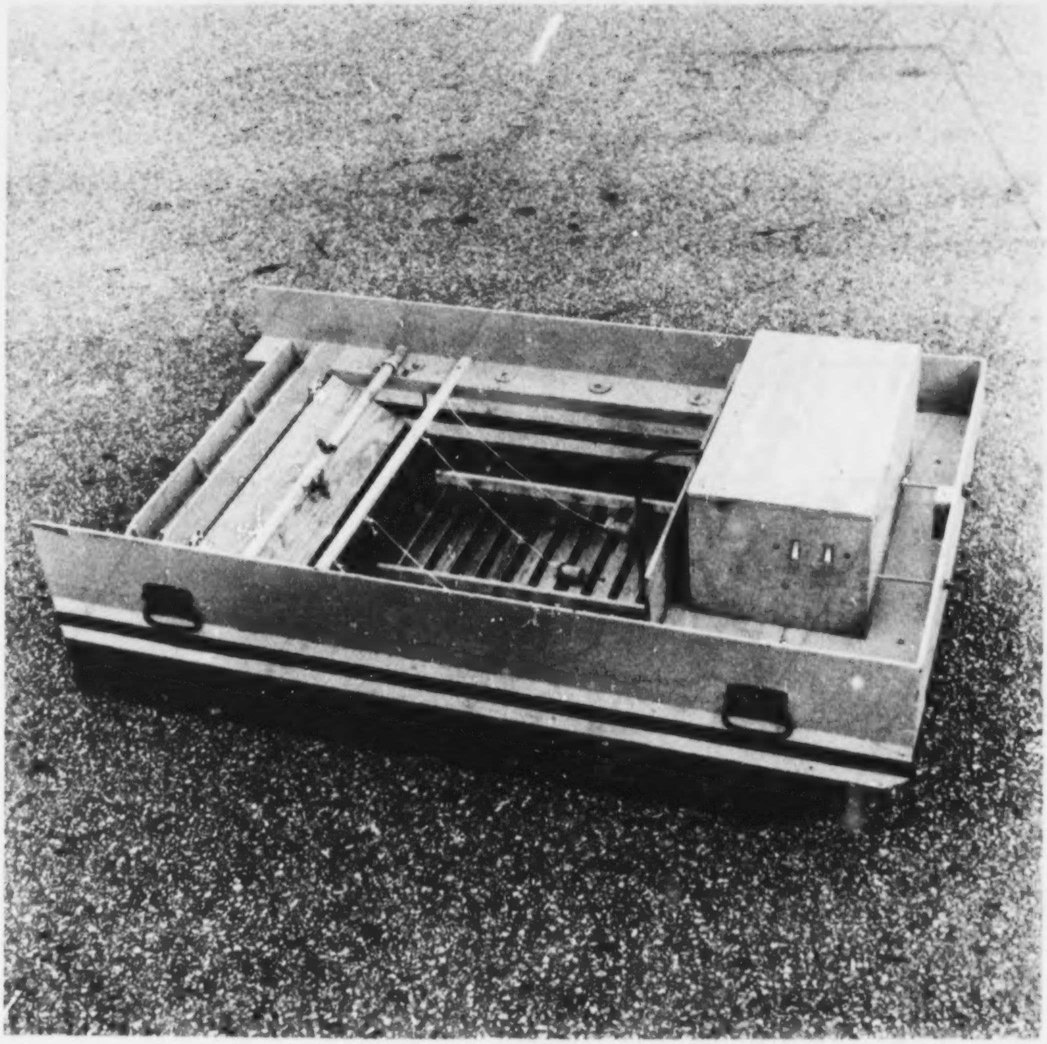
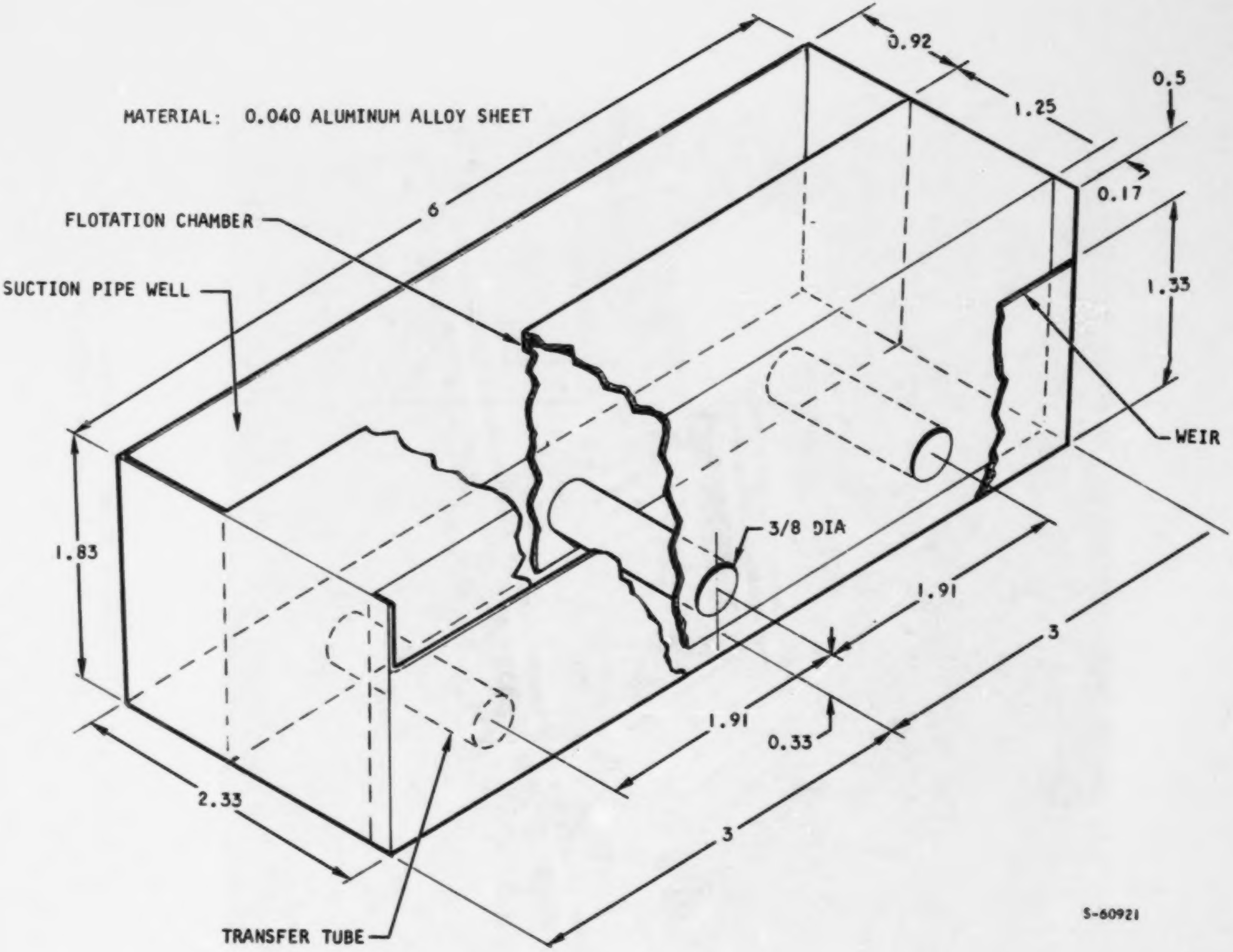


Figure 15. Oil Skimmer Barge 1/12th-Scale Model with Sloping Board Replacing Paddle Wheel



MATERIAL: 0.040 ALUMINUM ALLOY SHEET

Figure 16. Floating Weir Model (1/12-Scale)

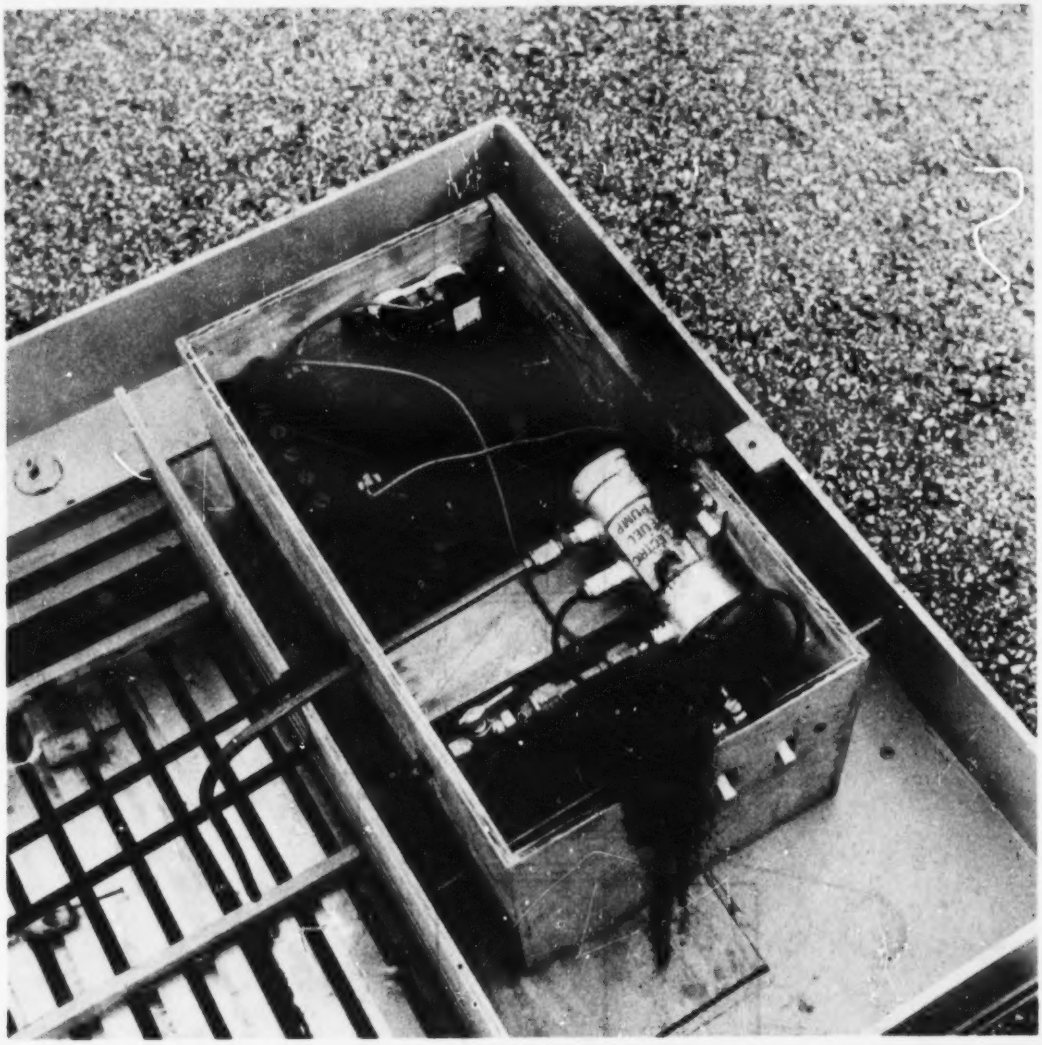


Figure 17. Oil Skimmer Barge 1/12th-Scale Model Paddle Wheel Drive and Weir Pumping Systems

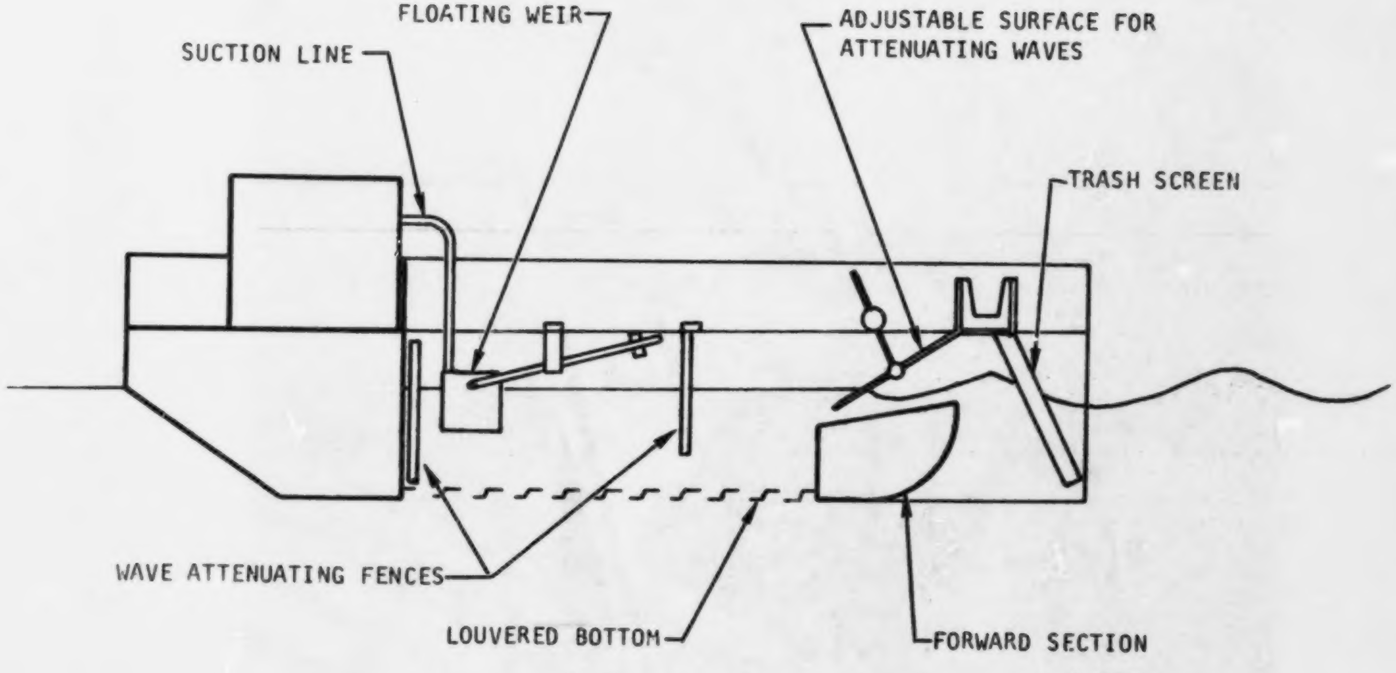


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Figure 18. Model Configuration during the Tests of January 12, 1970

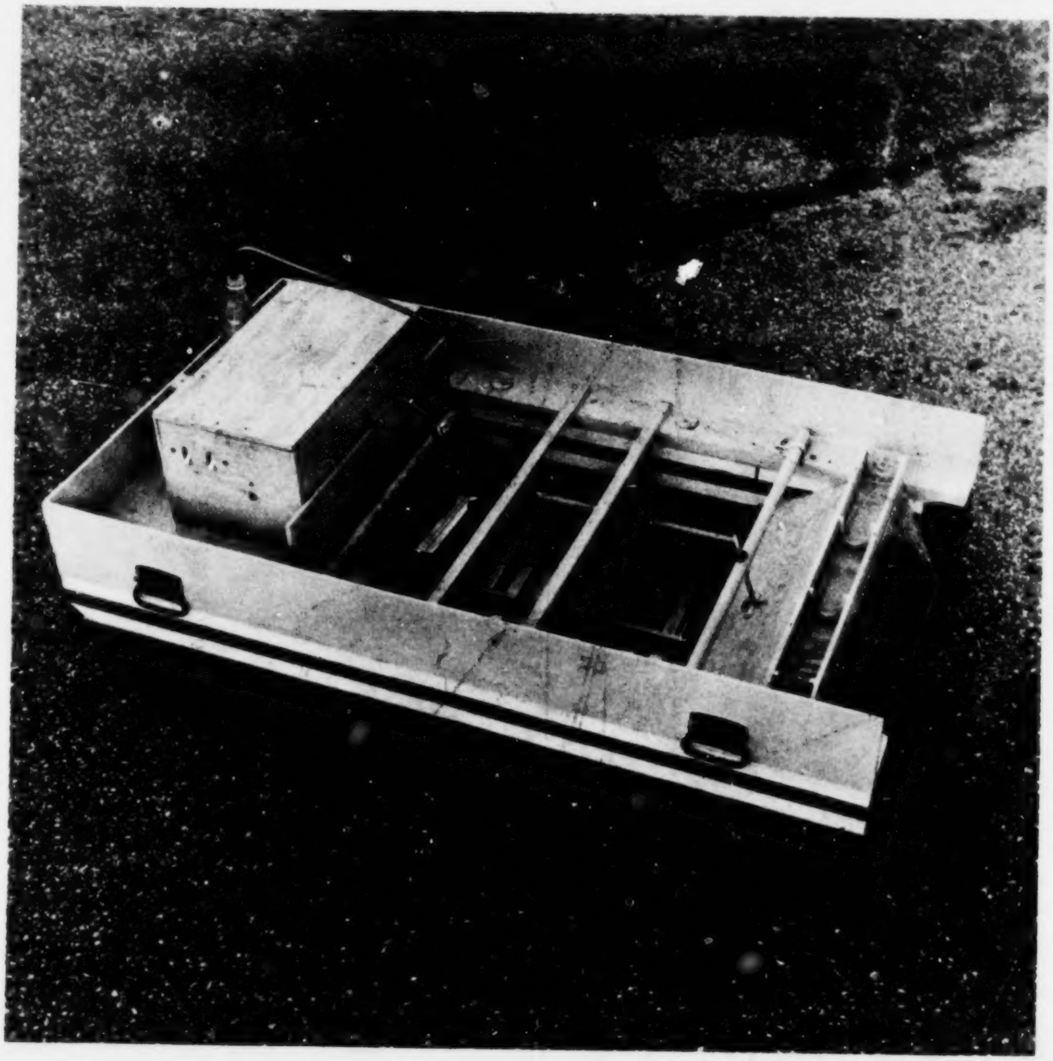

Figure 19. Oil Skimmer Barge 1/12th-Scale Model

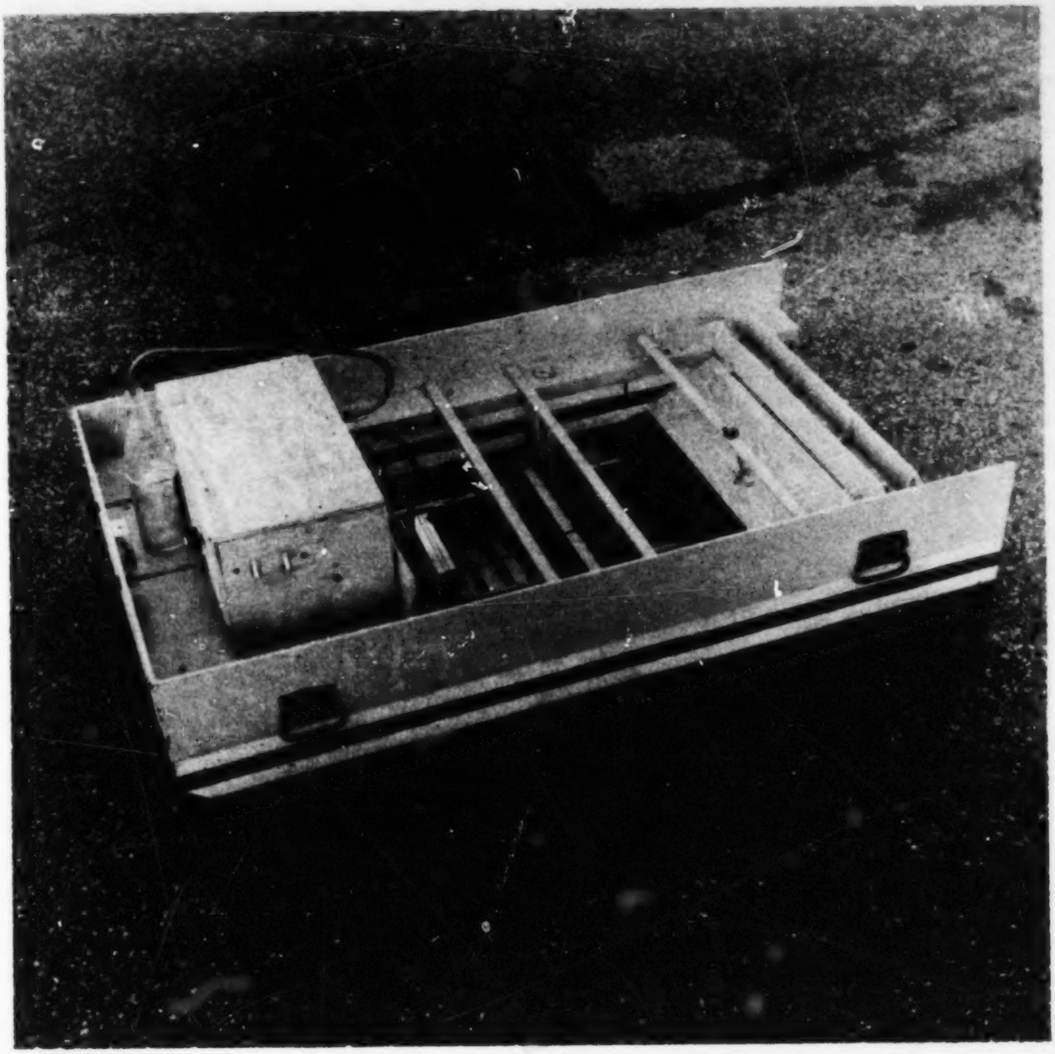

Figure 20. Oil Skimmer Barge 1/12-Scale Model

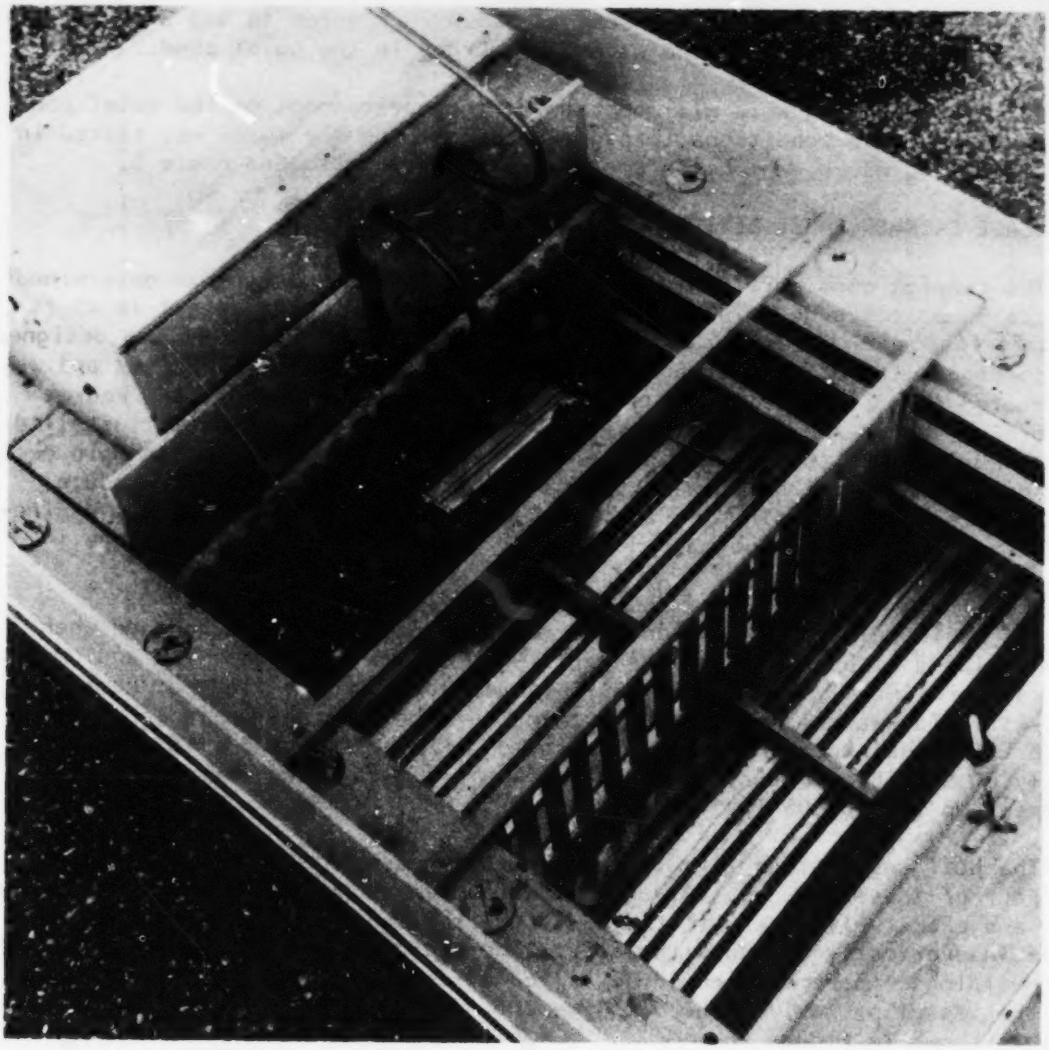

Figure 21. Oil Skimmer Barge /12th-Scale Model

The model was towed under a number of conditions and it was observed by film review that the waves around the weir in the quiet pond were smaller after the wave fences were installed.

The following conclusions were made:

(a) The wave attenuating fences, as shown in Figures 18 and 21, visually appeared to reduce the waves and surges in the quiet pond.

(b) The floating weir will operate in the environment of the quiet pond under sea conditions through Sea State 3 as the model was tested in 4-in. waves, which, to scale, are equivalent to Sea State 3.

FULL-SCALE SKIMMER BARGE DESIGN AND CONSTRUCTION

The general configuration of the full-scale skimmer barge was determined from the model tests described in the previous section. The vessel is 45 ft long, 26 ft across the beam, and 8 ft from keel to main deck. It was designed in accordance with U.S. Coast Guard requirements for steel tank barges and was constructed primarily of 1/4-in. steel plates at Todd Shipyards, San Pedro, California. While the original design concept included permanently installed pumping equipment with a single diesel engine power source below the main deck in an engine room, the barge was built without these refinements to reduce cost. Instead, all pumping was accomplished by means of rental diesel engine-driven units mounted on the main deck. All of the piping was, therefore, placed above the main deck.

The basic hull shown in Figure 22 weighed 59,000 lb at launch and when fully equipped with all the wave suppressors, weirs, and processing equipment, weighed approximately 90,000 lb. At this weight, it would float at nominally the 2-ft 10-in. waterline. A displacement curve for the barge is shown in Figure 23. To sink to the nominal operational waterline of 5 ft 0 in., approximately 80,000 lb of ballast water had to be added to bring the vessel displacement up to 170,000 lb.

The hull was divided into 11 watertight compartments as shown in Figure 24. Four of these (3P, 3S, 4P, and 4S) were used as reserve buoyancy compartments and check valves were installed in their bilge pipes so that they could not be inadvertently filled with water. The engine room was similarly protected. The remaining compartments could be filled or emptied at a rate of 150 gpm to trim the vessel properly. The displacement of each of the individual compartments is shown in Figure 25.

A simplified piping schematic diagram was shown in Figure 1 and the detailed pumping arrangements are shown in Figure 26. Any one of the three weir pumps can also serve for bilge pumping and ballast pumping through connections with the bilge and ballast manifolds. The oil transfer pump is also connected to the seawater inlet so that it can be used as a source of high-pressure (60 psi) water for general purposes such as washdown. Underwater viewing ports were installed in compartments 3S and 4P.

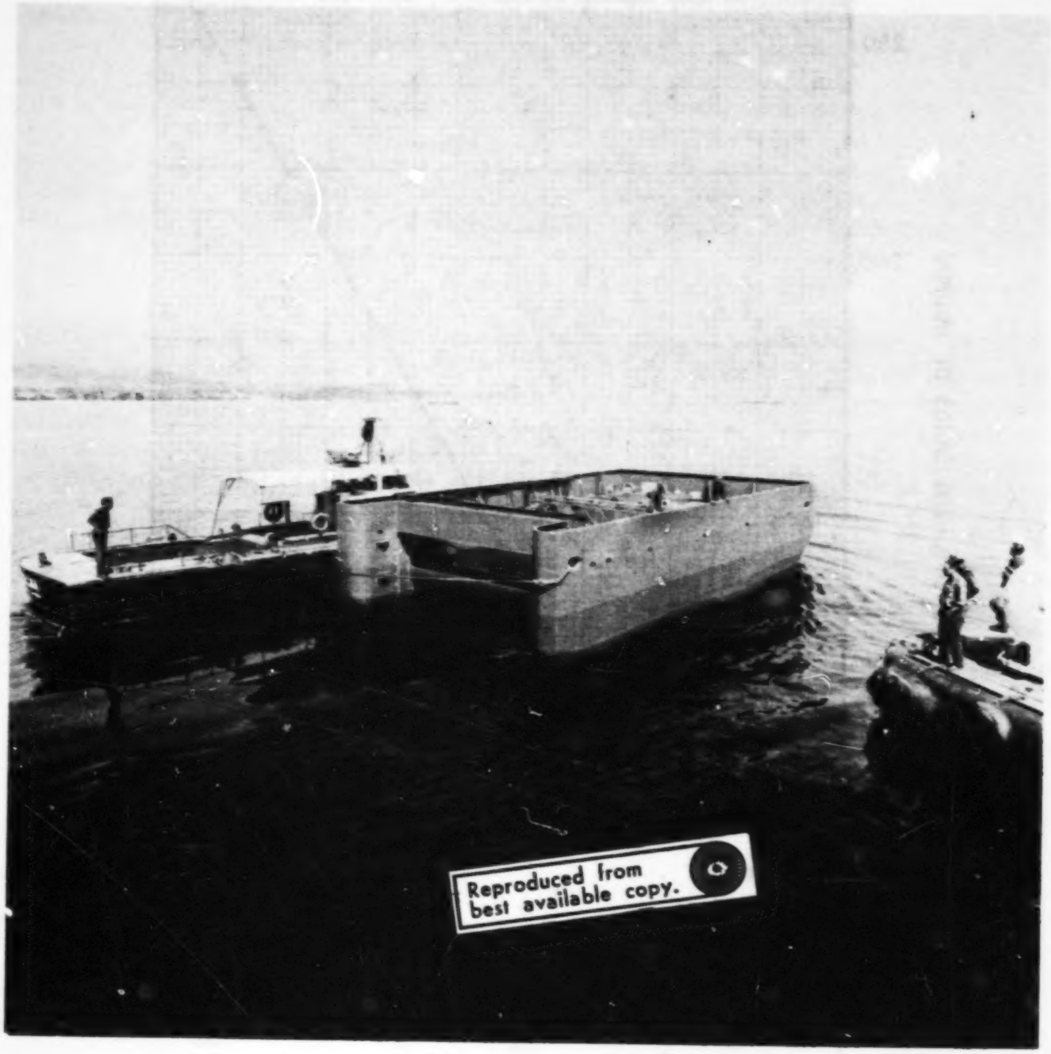

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Figure 22. Skimmer Barge Basic Hull

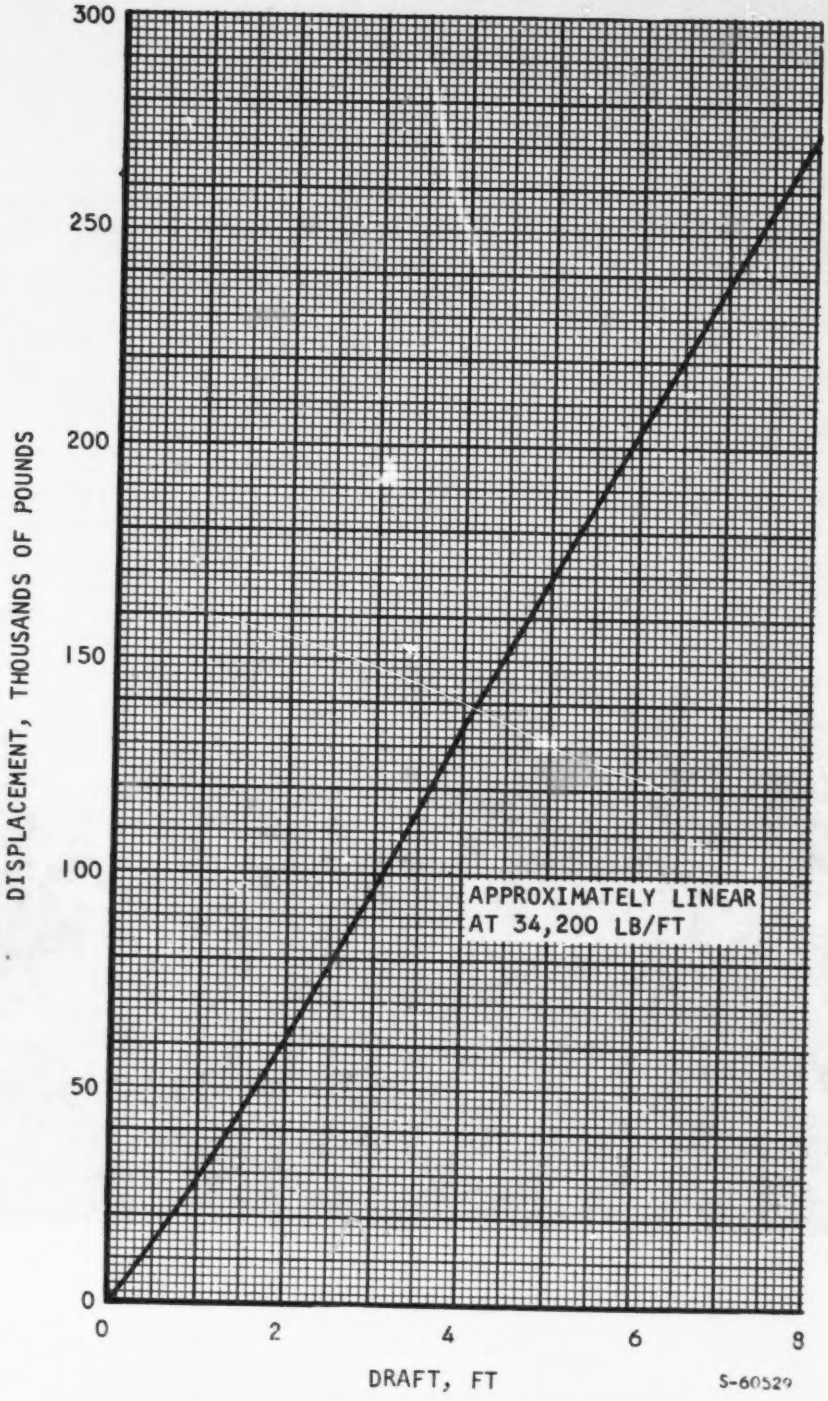


Figure 23. Skimmer Displacement Curve

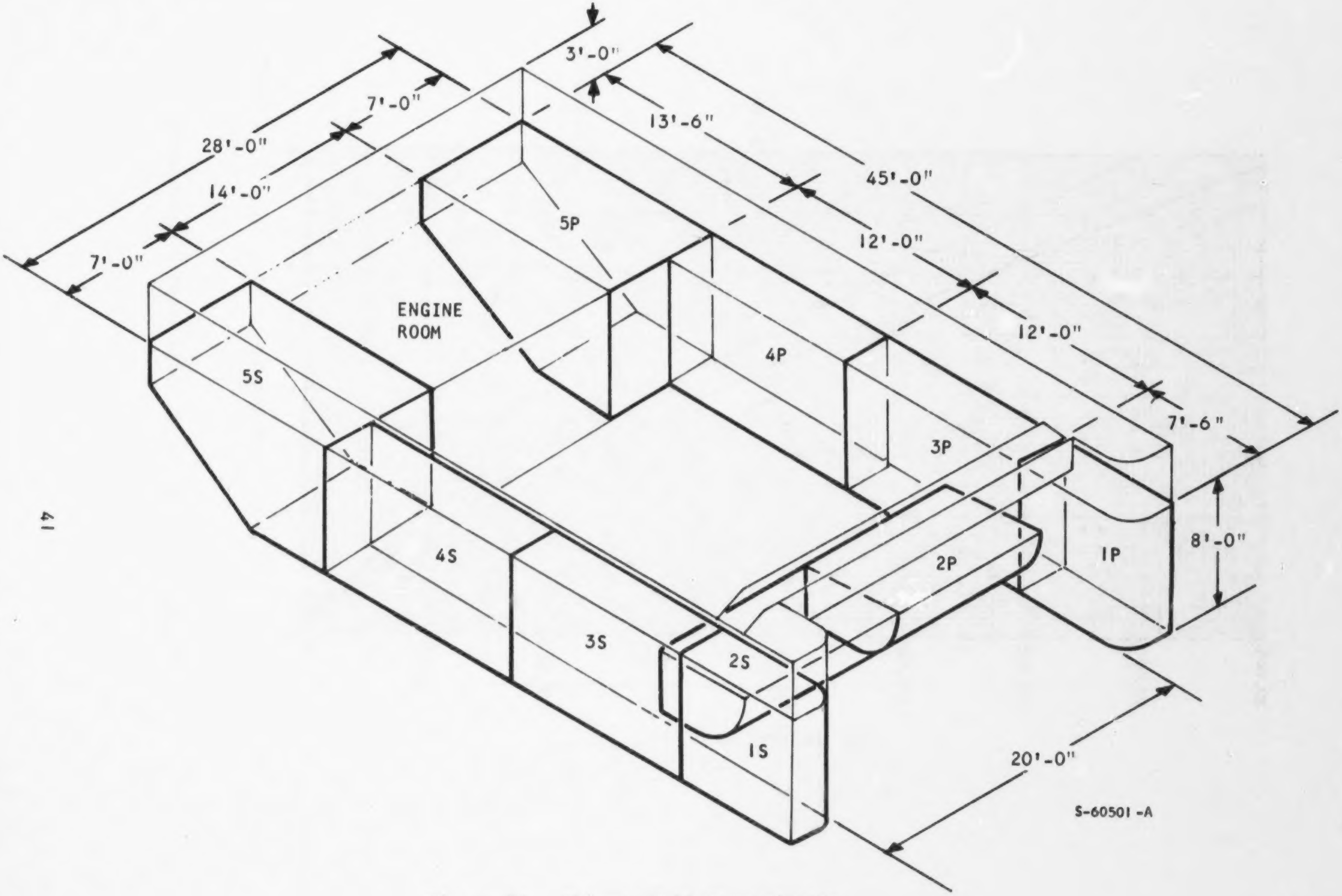


Figure 24. Skimmer Hull Compartments

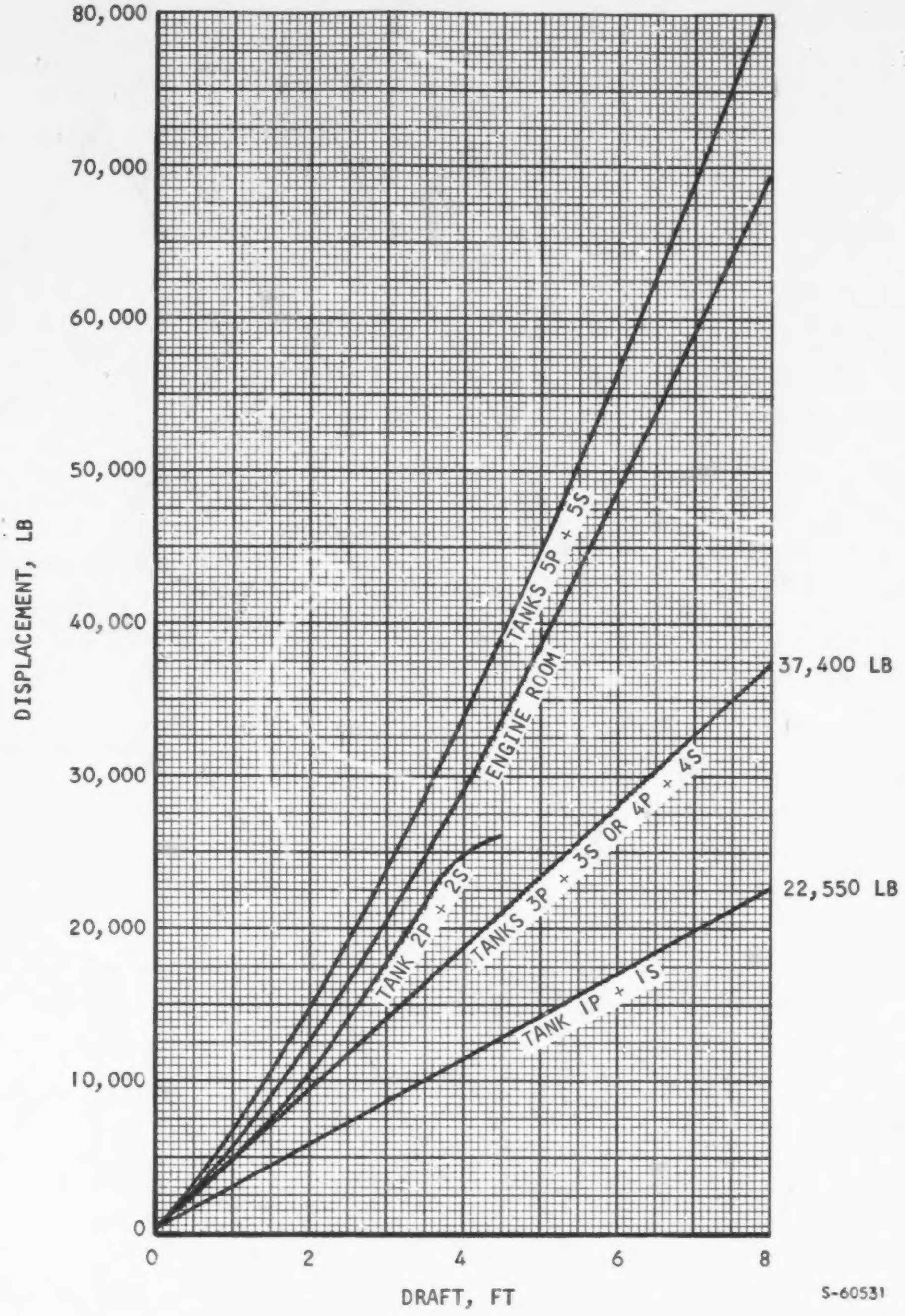


Figure 25. Individual Compartment Displacements

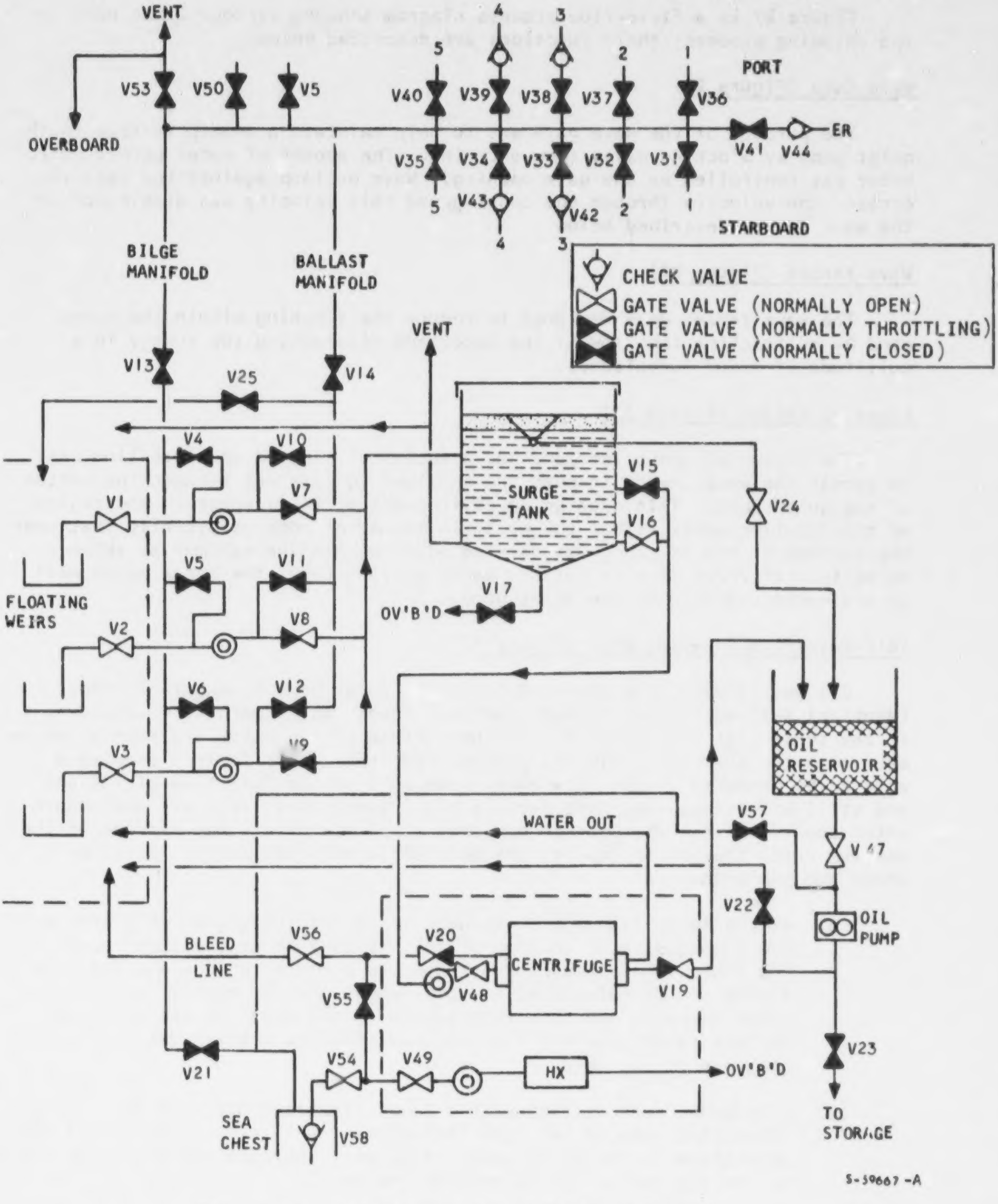


Figure 26. Oil Skimmer Barge Piping Schematic

Figure 27 is a fluid-flow process diagram showing various items used in the skimming process; their functions are described below.

Wave Gate (Figure 28)

The purpose of the wave gate was to help maintain a smooth surface in the quiet pond by blocking waves from entering. The amount of water permitted to enter was controlled by the gate opening. Wave buildup against the gate increased the velocity through the opening, and this velocity was dissipated in the wave fences described below.

Wave Fences (Figure 29)

The wave fences were designed to reduce the sloshing within the quiet pond by restricting the flow of the water and dissipating the energy in a multitude of minor turbulences.

Louvered Bottom (Figure 30)

The bottom of the quiet pond had a series of slotted openings (louvers) to permit the water taken in over the spillway to pass out through the bottom of the quiet pond. This created an environment of still water in the region of the floating weirs, since the water in the quiet pond, especially that near the surface at the aft end, was carried along within the skimmer at skimmer velocity. If there were no bottom, water passing under the barge would well up and cause currents in the quiet pond.

Self-Adjusting Floating Weir (Figure 31)

Oil was skimmed from the surface of the quiet pond by means of three identical self-adjusting, floating weirs. These weirs were self-adjusting in the sense that they would follow the surface of the water and skim at whatever rate the skimmed liquid was pumped from them. This feature enabled a weir to be operated at any flow rate, from zero to the full flow of 170 gpm and still effectively skim the surface oil. Under very light oil and smooth water conditions the weir can be operated at approximately one percent of the maximum rate, thereby increasing the weir efficiency (oil/water ratio) by these two phenomena:

(a) At the lower flow rates the weir is self-adjusting to skim only a few thousandths of an inch of the top surface of the quiet pond. The lower limit is dependent upon the surface tension and the condition of the quiet pond surface (waves and currents). At low flow rates the flow over the weir may be intermittent if the effect of surface tension or oil viscosity exceeds the average depth of submergence of the weir.

(b) A second effect is that with a lower flow rate over the weir for a given flow rate of oil into the skimmer, a thicker layer of oil will accumulate in the quiet pond. This will increase the oil/water ratio of the top surface as skimmed by the weir.

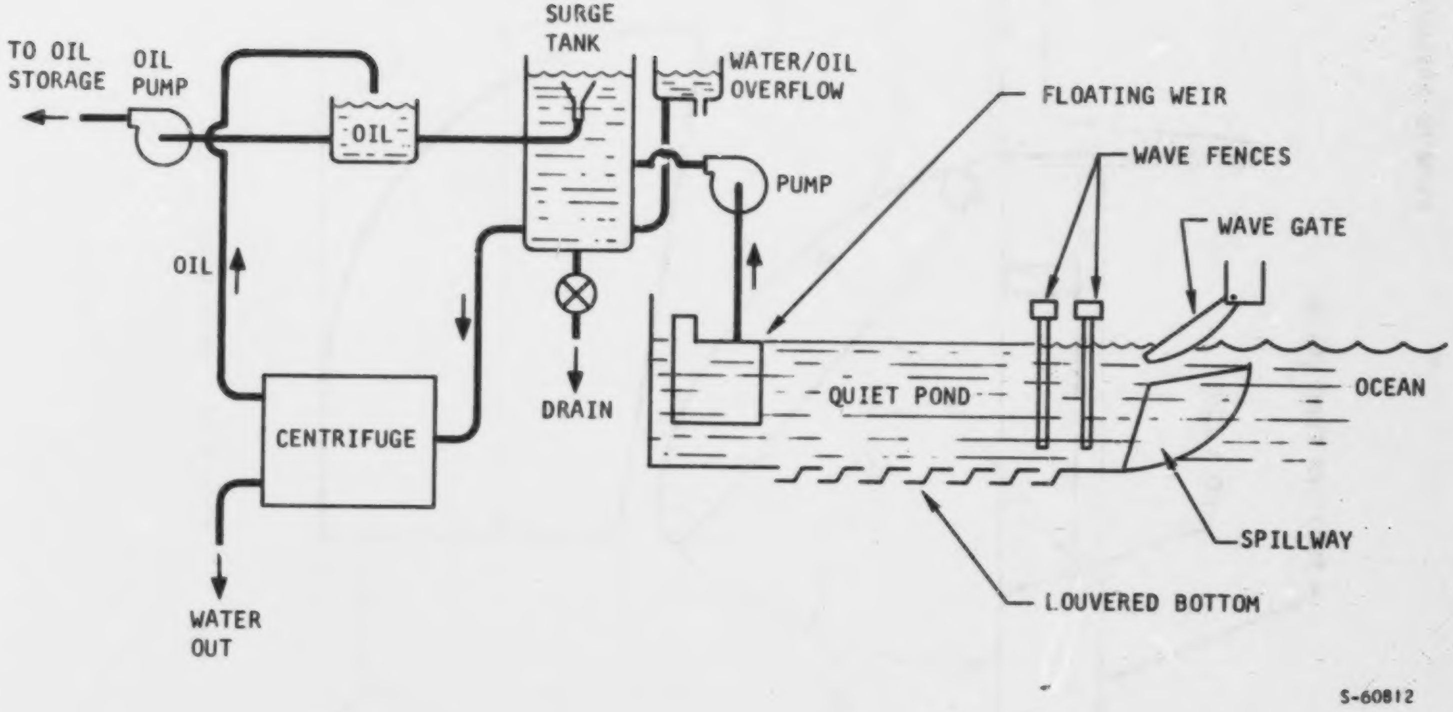


Figure 27. Fluid Flow Processing Diagram

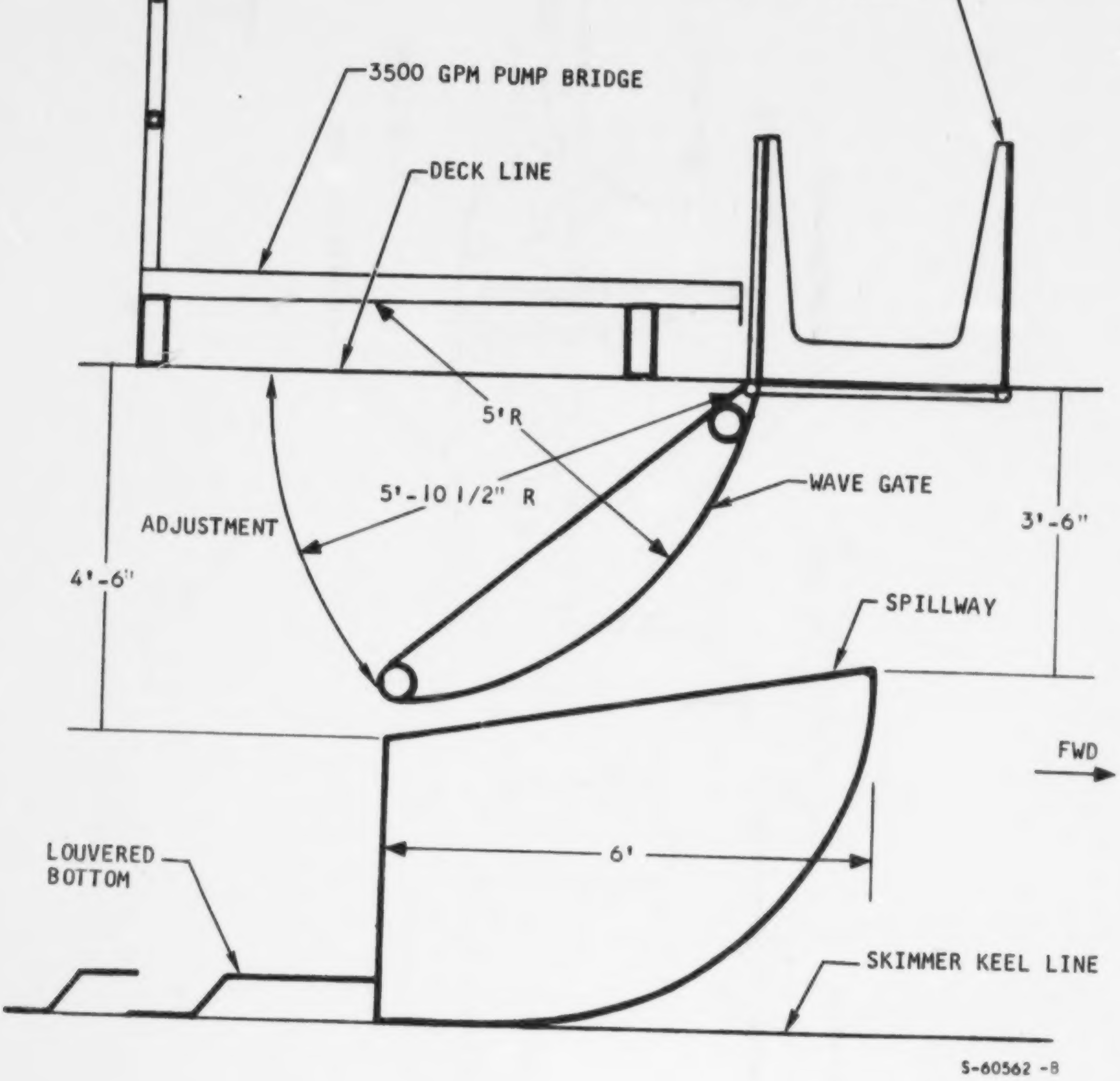


Figure 28. Wave Gate

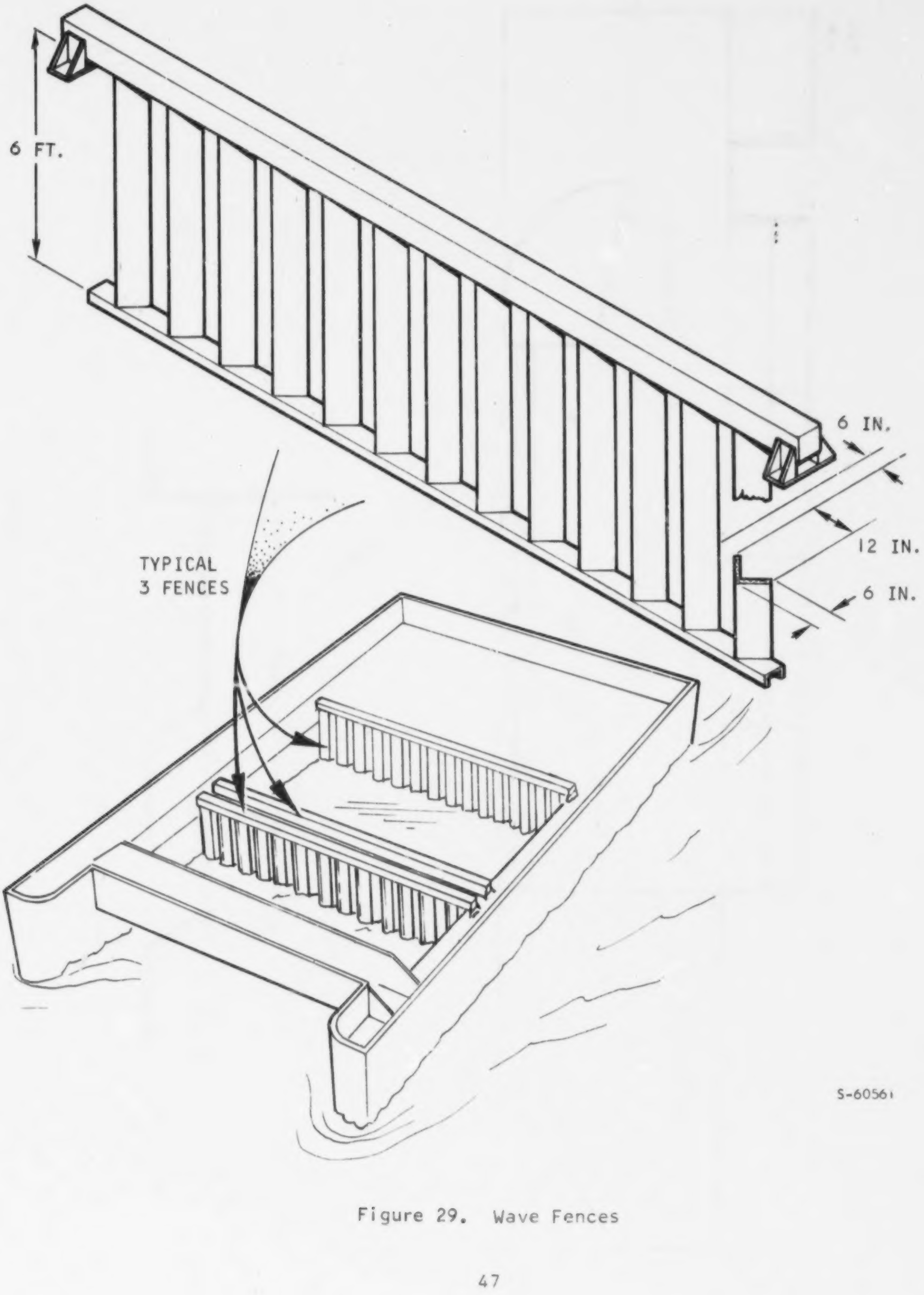


Figure 29. Wave Fences

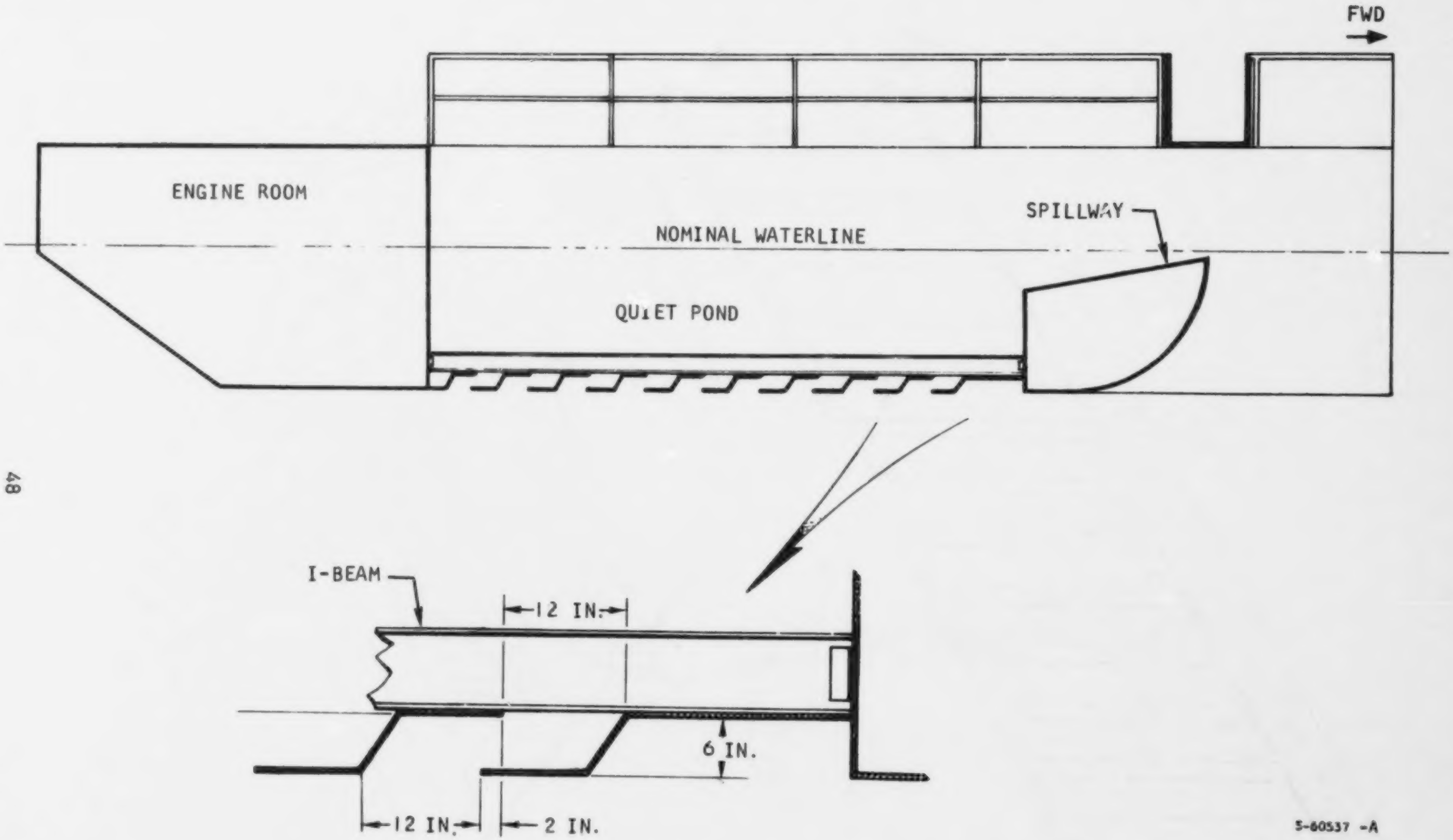


Figure 30. Louvered Bottom

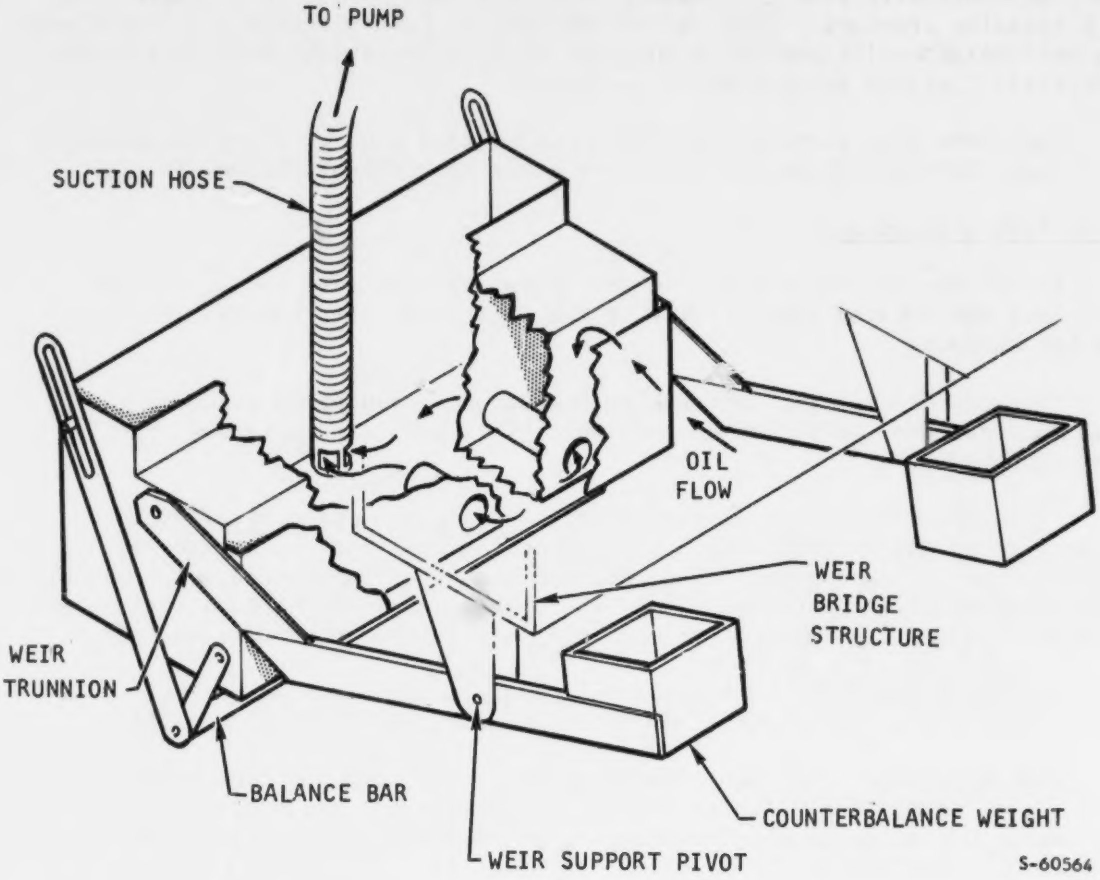


Figure 31. Self-Adjusting Floating Weir

Weir Pumping

Each weir was pumped by means of a diesel engine-driven 3-in. centrifugal trash pump of 170 gpm capacity. These pumps had a self-priming feature and would reprime if the weir were momentarily pumped dry. The weir was connected to the pump inlet by means of a 6-ft-long section of flexible hose that allowed the weir complete freedom of movement (Figure 32). During pumping this hose would automatically seek a minimum volume condition, since the interior was at a negative pressure. This caused the hose to run in a straight line between the weir attach point and the pump inlet pipe, while at the same time it was completely flexible as to changes in length.

The three weir pumping units were rented from John W. Stang Corporation of Orange, California and are more completely described in Figure 33.

Surge Tank (Figure 34)

All of the discharge from the weir pumps was fed into the surge tank. The inlet was located tangentially at the 4-ft level at a nominal 18 in. below the surface.

The liquid level in the surge tank was controlled by an overflow weir that was fed from the bottom of the tank. This permitted overflow of only the cleanest water.

The surface of the liquid in the tank tended to remain level as the barge pitched and rolled beneath it. Since the roll and pitch rates were so slow and the roll and pitch angles were of such small magnitude, no sloshing over the tank walls occurred. Also, in normal operation the tank surface was covered with a thick layer of viscous oil that further reduced sloshing.

Oil was drawn from the circular oil overflow weir on the vertical axis of the tank where the influence of pitch and roll had the minimum effect.

The centrifuge inlet water was drawn from the bottom of the surge tank at rates up to 500 gpm. The centrifuge effluent water was discharged into the bottom of the quiet pond so that any entrained oil could be reprocessed back through the system.

Oil Transfer Pump

The surge tank oil overflow and the centrifuge discharge oil were collected in an oil transfer barrel at the inlet of the oil transfer pump. This pump, described below, transferred the oil to forward end of the skimmer (for closed-circuit skimmer testing), or to oil-receiving barrels or tanks.

Oil transfer pump characteristics are as follows:

Prime mover	Petter Type ABI Diesel Engine
Pump	Roper Model 3600 GHB

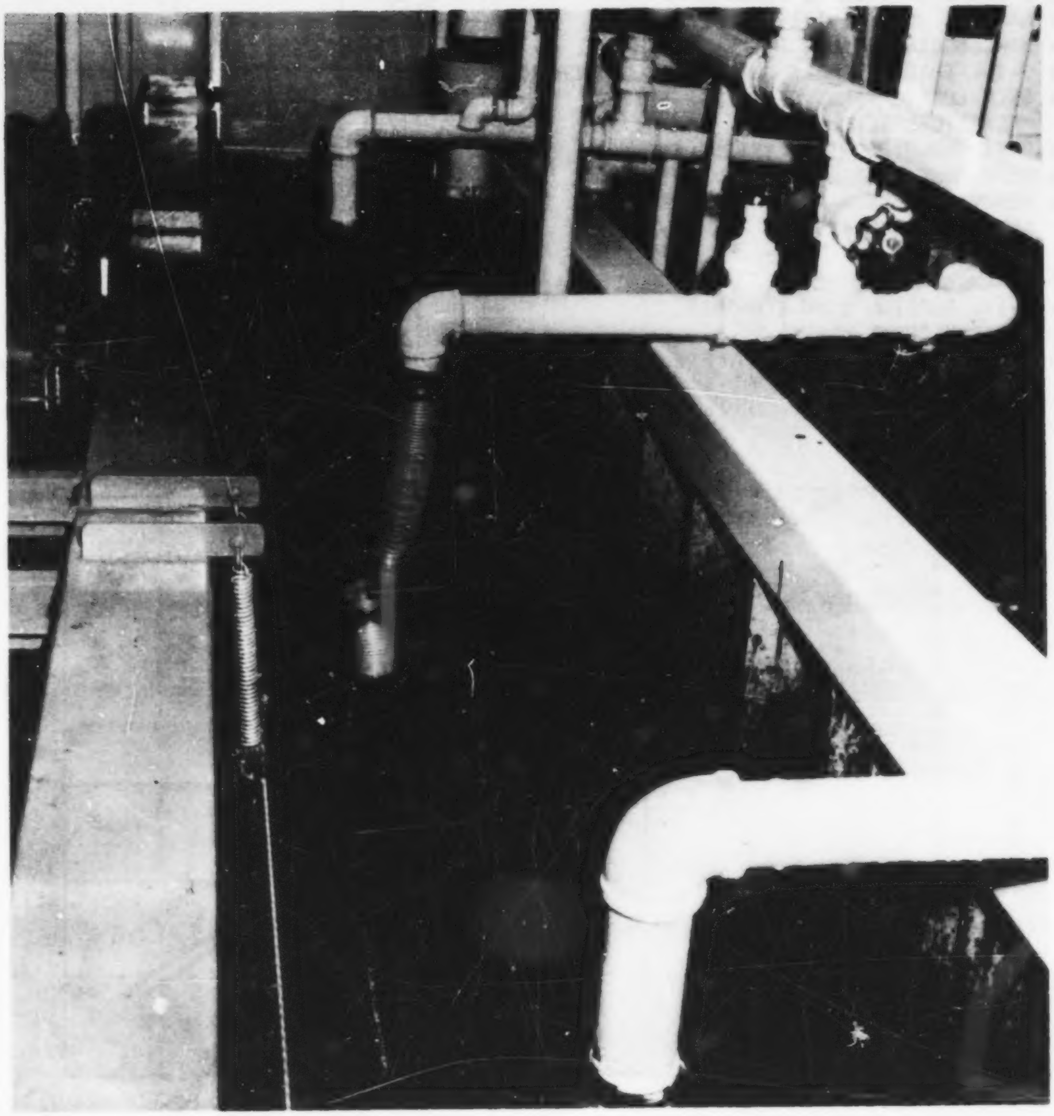


Figure 32. Weir Pumping

A. CHARACTERISTICS

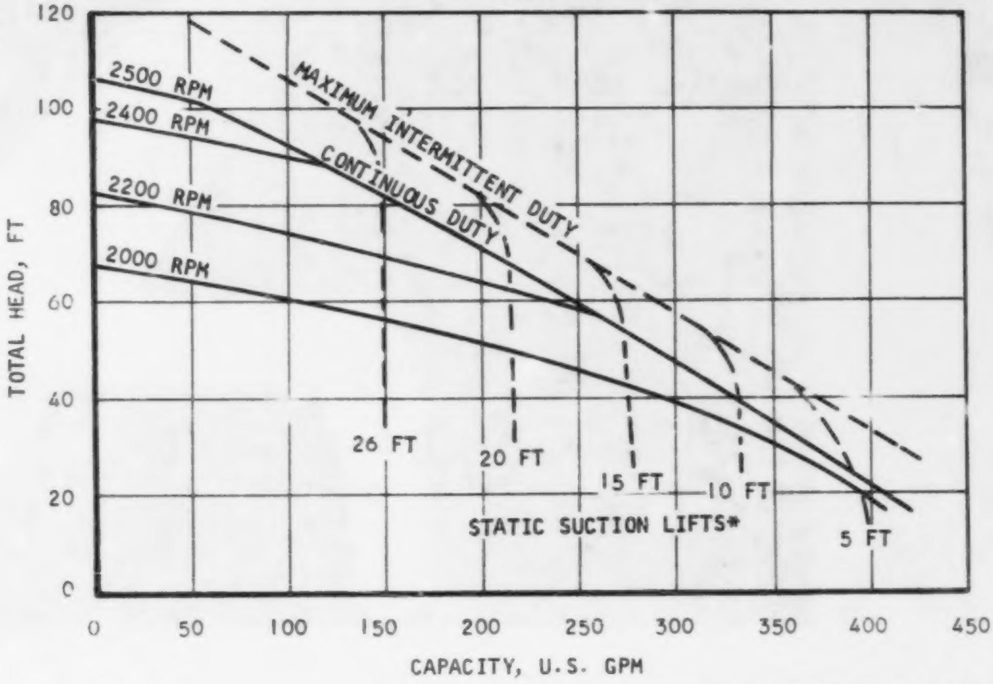
- 3-IN. SELF-PRIMING TRASH PUMP
- HANDLES UP TO 1-1/2-IN. DIA SOLIDS
- NONCLOGGING VOLUTE PRIME SYSTEM
- 3-IN. THREADED MALE SUCTION AND DISCHARGE
- SELF-LUBRICATING, STAINLESS STEEL, MECHANICAL SEAL
- BASE MOUNTED WITH LIFTING EYE
- HEAVY DUTY IMPELLER AND VOLUTE
- REMOVABLE ELBOW AND COVER FOR ACCESS TO ALL WORKING PARTS FOR CLEANOUT AND MAINTENANCE
- RENEWABLE WEAR PLATE
- 3-IN. SUCTION LINE STRAINER
- SUCTION CHECK VALVE
- HAND OPERATED, 1-1/2 IN. FILLER PLUG

B. PERFORMANCE TABLE*

CAPACITY, U. S. GPM						
TOTAL HEAD		TOTAL STATIC SUCTION LIFT, FT				
FT	PSI	5	10	15	20	25
30	13.0	372	333	278	217	-
40	17.3	334	332	276	217	150
50	21.6	290	290	275	216	150
60	26.0	248	248	248	216	150
70	30.3	200	200	200	200	150
80	34.6	159	159	159	159	149
90	39.0	113	113	113	113	113
100	43.3	70	70	70	70	70

*Continuous service (governed throttle)

C. PERFORMANCE CURVES



*BASED ON NOMINAL SIZE SUCTION LINE 5 FT LONGER THAN STATIC SUCTION LIFTS SHOWN.

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Figure 33. Weir Pumping Unit Performance (J. W. Stang Model 3CR18EL)

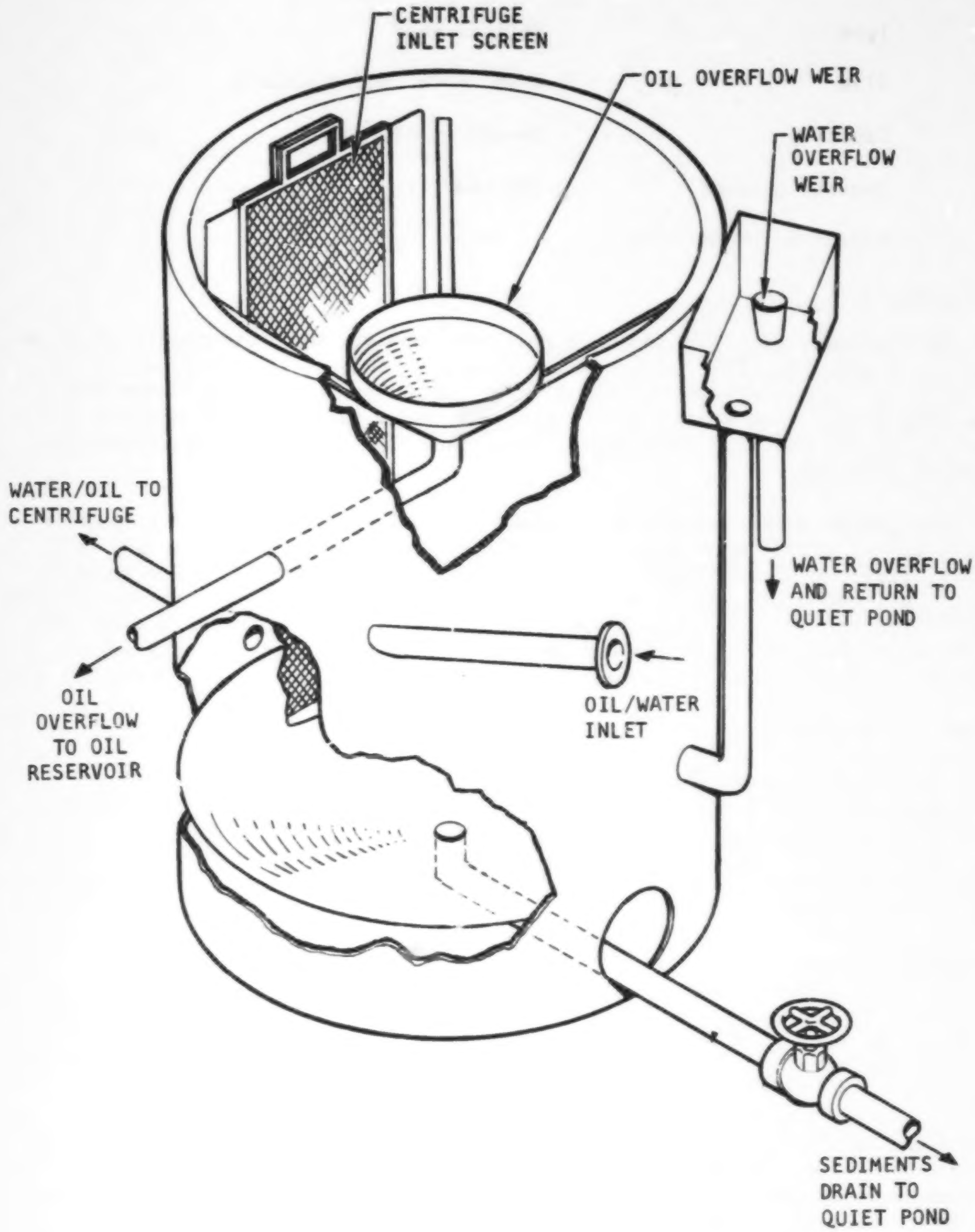
CENTRIFUGE INLET SCREEN
OIL OVERFLOW WEIR
WATER OVERFLOW WEIR
WATER/OIL TO CENTRIFUGE
WATER OVERFLOW AND RETURN TO QUIET POND
OIL/WATER INLET
OIL OVERFLOW TO OIL RESERVOIR
SEDIMENTS DRAIN TO QUIET POND

Figure 34. Surge Tank

S-60563-A

Type	Helical gear
Size	2-in. inlet and discharge
Capacity	60 gpm at 500 rpm
Operating speed	500 rpm
Relief valve setting	60 psig

Paddle Wheel

On September 16, 1970 the wave gate was replaced with the paddle wheel as shown in Figure 35. This device was designed to provide a pumping action at the entrance to the skimmer to sweep in oil when the skimmer was stopped or traveling at very low speeds and to act as a check valve for oil already in the quiet pond. It also reduced the effect of waves entering the skimmer by breaking them up.

The paddle wheel was driven by means of a small diesel engine through a V-belt drive, a 30:1 worm gear speed reducer, and a chain drive. The V-belt sheave sizes could be changed for coarse speed selection, and a fine adjustment of 4:1 could be made by adjustment of the engine governor. The centerline was located 26 in. aft of the lip of the spillway, as shown in Figure 36. The paddle wheel was vertically adjustable with a nominal clearance of 1 in. between it and the top of the spillway.

SKIMMER BARGE TESTS

The skimmer barge, incorporating the centrifuge described in Section VII, was tested at sea as described in Section VIII. The tests demonstrated the feasibility of skimming oil from the ocean surface. The following is a discussion of the test results (see Section VIII) as they pertain to the skimmer barge, and describes notable features, problem areas, and possible improvements that could be made.

Wave Gate

Prior to installation of the wave gate on September 16, 1970 conditions in the quiet pond were such that when the barge was towed upwind at 2 to 5 knots in Sea State 3, the weirs sloshed and rocked to such an extent as to be ineffective as skimming devices. After installation of the wave gate the weirs could be operated going upwind at speeds up to 5 knots under any sea conditions experienced during the test program (Sea State 0 to Sea State 3). When closed, the wave gate also afforded complete protection to the quiet pond during high speed towing to the deployment site. Under many other conditions, however, the wave gate tended to increase the disturbances in the forward end of the quiet pond and also was capable of causing a bow wave from wave reflections off the submerged gate. This gate should be readily adjustable under any sea conditions and forward velocity to obtain the maximum benefit, which would require a hydraulic cylinder, rack and pinion, jackscrews, or some

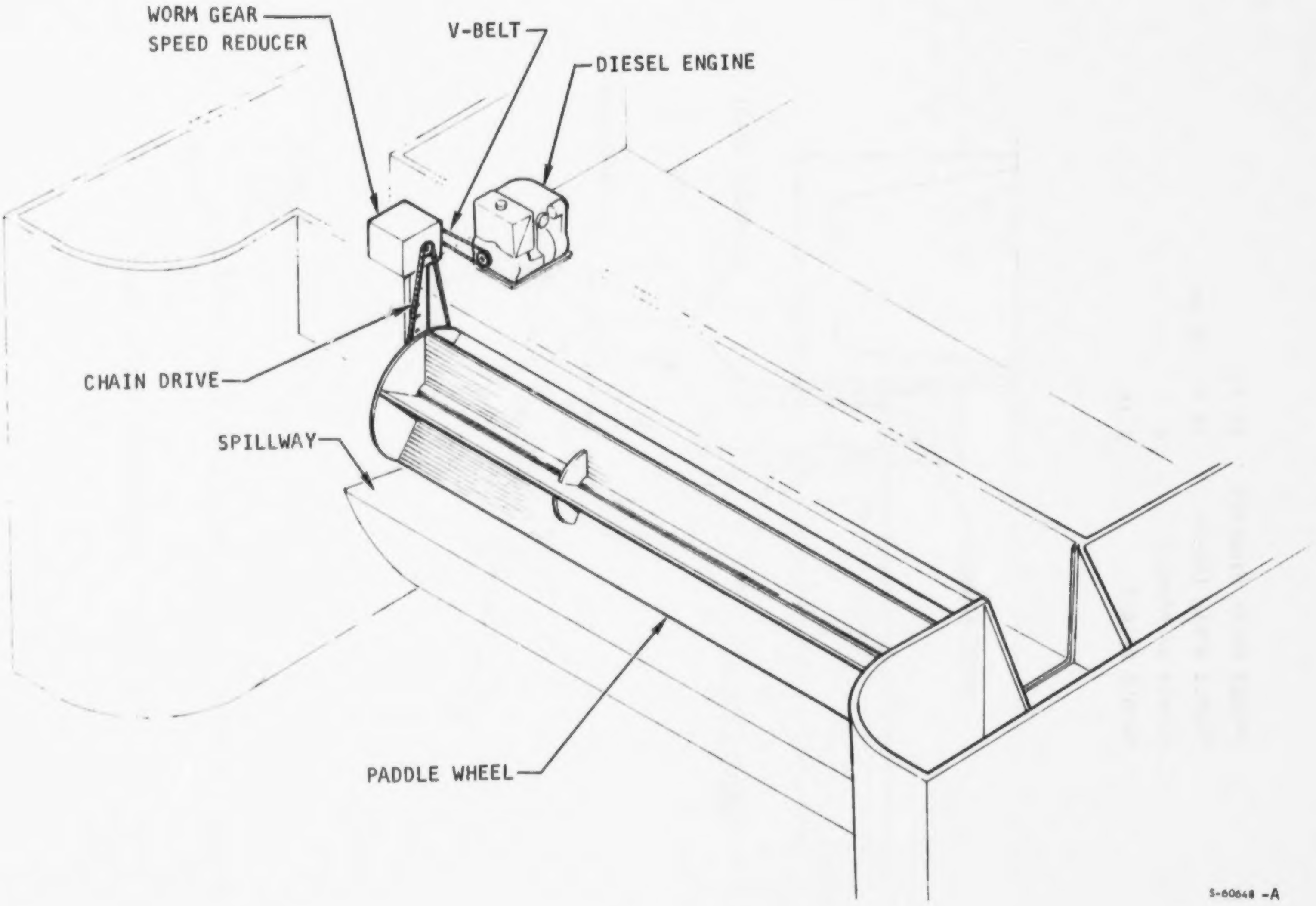

Figure 35. Paddle Wheel Installation

PADDLE WHEEL DIAMETER	36 IN.
PADDLE WHEEL LENGTH	18 FT. 10 IN.
NUMBER OF PADDLES	6
PADDLE HEIGHT	8 IN.

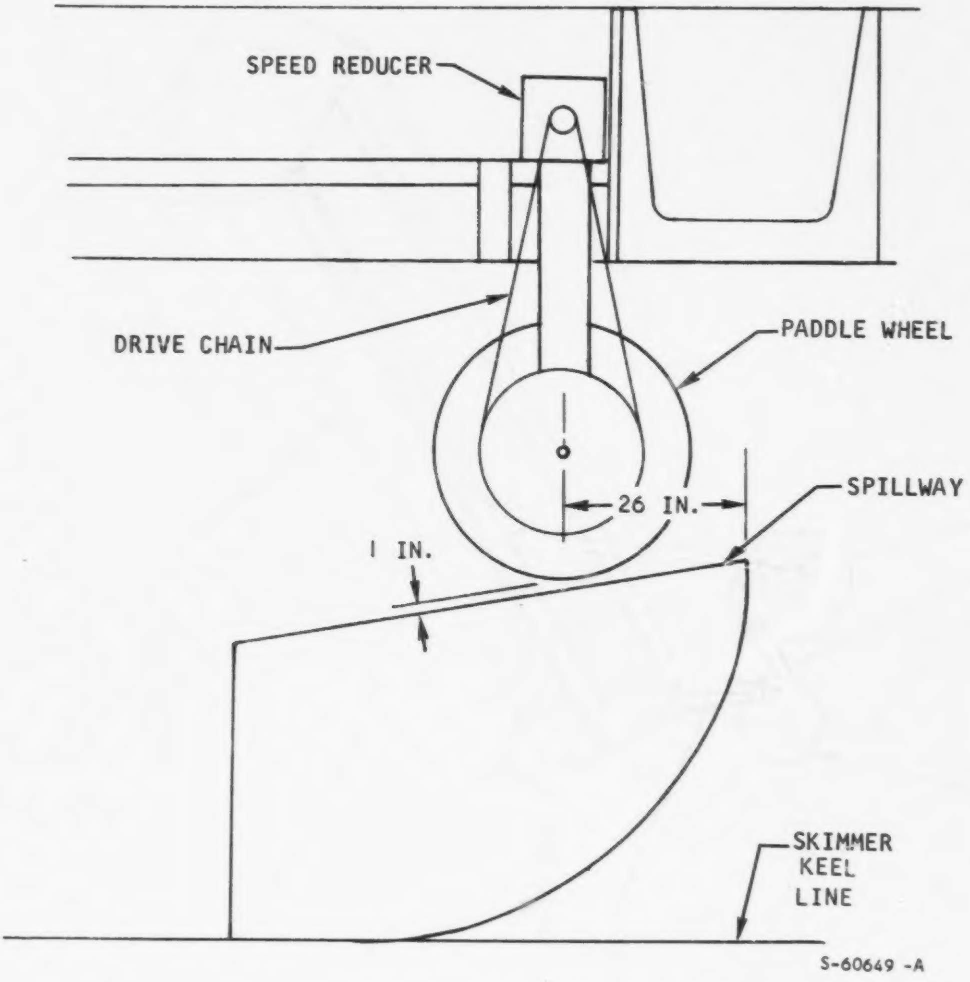

Figure 36. Side View of Paddle Wheel

similar device. The present model had a worm-gear cable hoist to lift the gate; it is then bolted in the desired position. This could not be done when waves were striking the gate. Possibly the addition of devices to break up the wave so it is not reflected from the smooth surface would enhance its performance.

Wave Fences

During the first at-sea test with the skimmer barge (skimming tow tests on June 3, 1970) it was observed that waves entering the skimmer or generated within the skimmer by "sloshing" reflected off the aft bulkhead of the quiet pond and increased the surface disturbance in the quiet pond. Also, waves directed at the aft corners of the quiet pond would splash up over the deck. After the wave fence was installed just ahead of the aft bulkhead, the wave reflections no longer occurred and water was not observed to splash up on the afterdeck from waves in the quiet pond.

Use of the wave fences in the forward part of the quiet pond markedly increased the local disturbance, but the overall effect was the reduction in size of the waves.

Louvered Bottom

Water in the quiet pond was carried along with the barge, and it was repeatedly observed that objects or oil floating on the surface of the quiet pond had practically no velocity with respect to the barge, even when the barge was traveling through the water at speeds above 5 knots. It was observed through the aft underwater viewing port that submerged particles had very low velocity and a single particle could be observed for several seconds within the limited range of view of the port. The oil on the water surface in front of the floating weirs moved slowly toward the weirs as the surface was drawn off. These observations were in agreement with observations made during the model test with the louvered bottom.

Self-Adjusting Floating Weir

Proper operation of the weir was dependent upon a rather delicate initial balance, which was adjusted by means of a weight bar (Figure 31). Once adjusted for a particular weir, the adjustment never needed to be changed. A second adjustment was the counterbalance weight, which tended to make the weir assembly float higher or lower in the water. This adjustment did have to be changed occasionally, primarily to allow for changes in average wave conditions in the quiet pond.

Although a weir operated for hours unattended, an operator was stationed on the weir bridge to tend the weirs. His principal occupation was to remove kelp and other floating objects from the quiet pond and occasionally to change the trash screens in the weir inlet.

When a weir was not in use it was hoisted free of the water by means of a permanently attached hand winch assembly (Figure 37). This was done to prevent excessive movement during high speed towing and rough sea conditions.

Weir Pumps

During the entire test program, there was never a need to disassemble any of these pumps for cleaning, although they did have an easily removable face plate to facilitate cleaning. (The diesel engines that drove these pumps also performed without malfunctions for the entire test program.)

This type of centrifugal pump, although ideally suited as far as transferring the oil/water mixture from the weir to the surge tank, tended to emulsify the oil. This was not a significant problem with the thicker oils, but when 35° API gravity oil was used, a large amount of oil was observed in the surge tank overflow. Although this was still readily removed by the centrifuge, it would be more convenient to remove all the oil possible in the surge tank.

Surge Tank

The location of the inlet caused mild circular circulation within the tank, with the oil migrating to the center top and the cleaner water to the bottom outside. This circulation was later obstructed somewhat by the installation of screens across the outlet pipes (Figure 38) to prevent the flow of kelp pieces and other undesirable objects into the centrifuge. This tank inlet also seemed to be a little too close to the top and unnecessarily disturbed the surface water.

The overflow weir allowed only the cleanest water to be returned to the quiet pond. In fact, under low flow conditions (50 gpm) the surge tank overflow was visually judged to contain less than 25 mg/l since samples of the water taken in 4- or 16-oz jars showed no oil film on the water surface. This water was returned to the quiet pond, as was the centrifuge discharge water, so in the event that excessive oil were present it would be reprocessed and removed.

During operation, the flow demands of the centrifuge and the output of the weir pumps had to be adjusted so that the weir pumps always pumped at a slightly higher rate than required by the centrifuge in order to assure a full surge tank. The excess was handled by the surge tank overflow weir.

When a significant amount of oil was collected on top of the water surface in the surge tank, it was drawn off by means of a centrally located conical overflow weir. This oil drained through a 3-in. pipe into the oil transfer barrel.

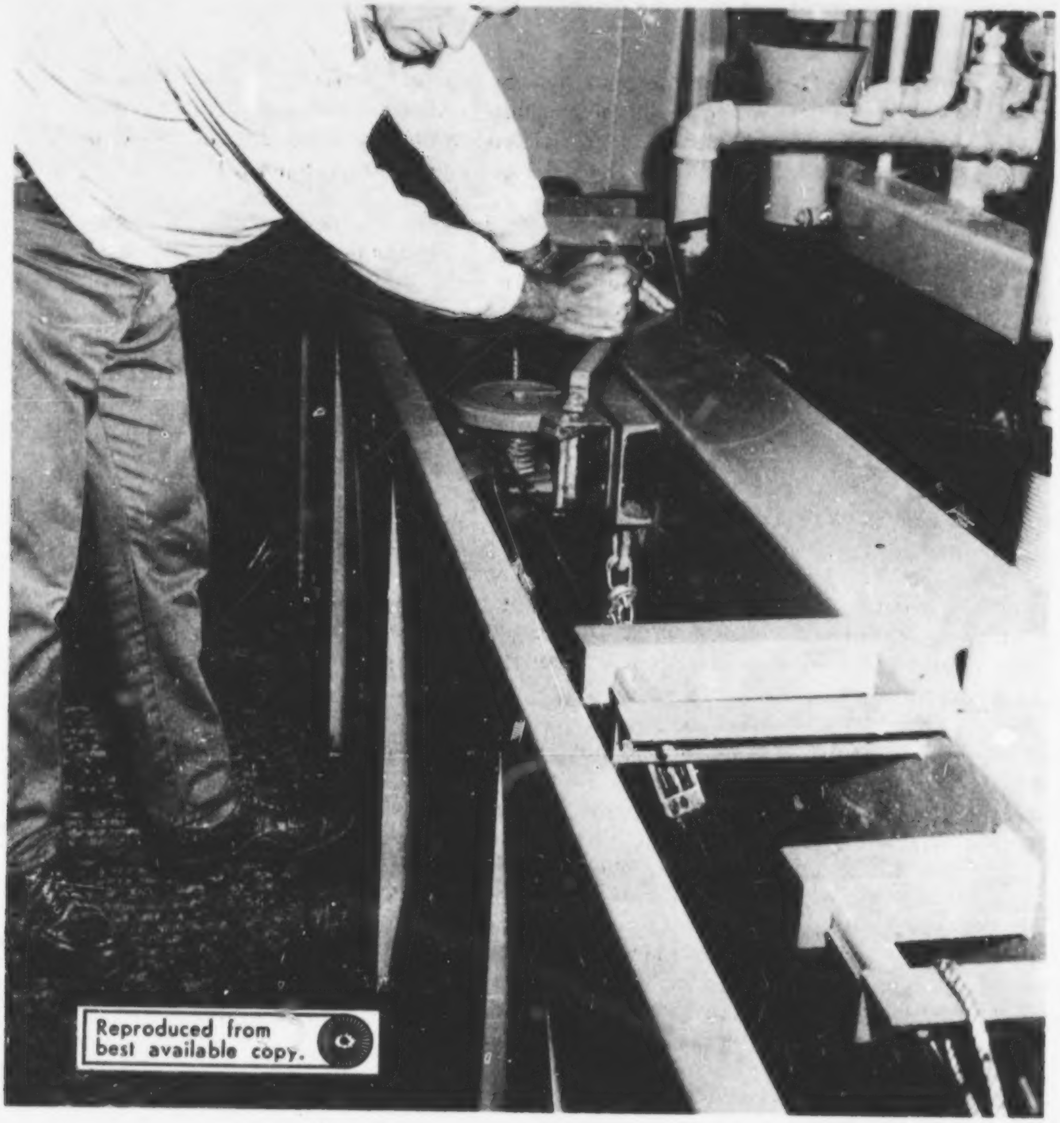

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Figure 37. Weir Winch

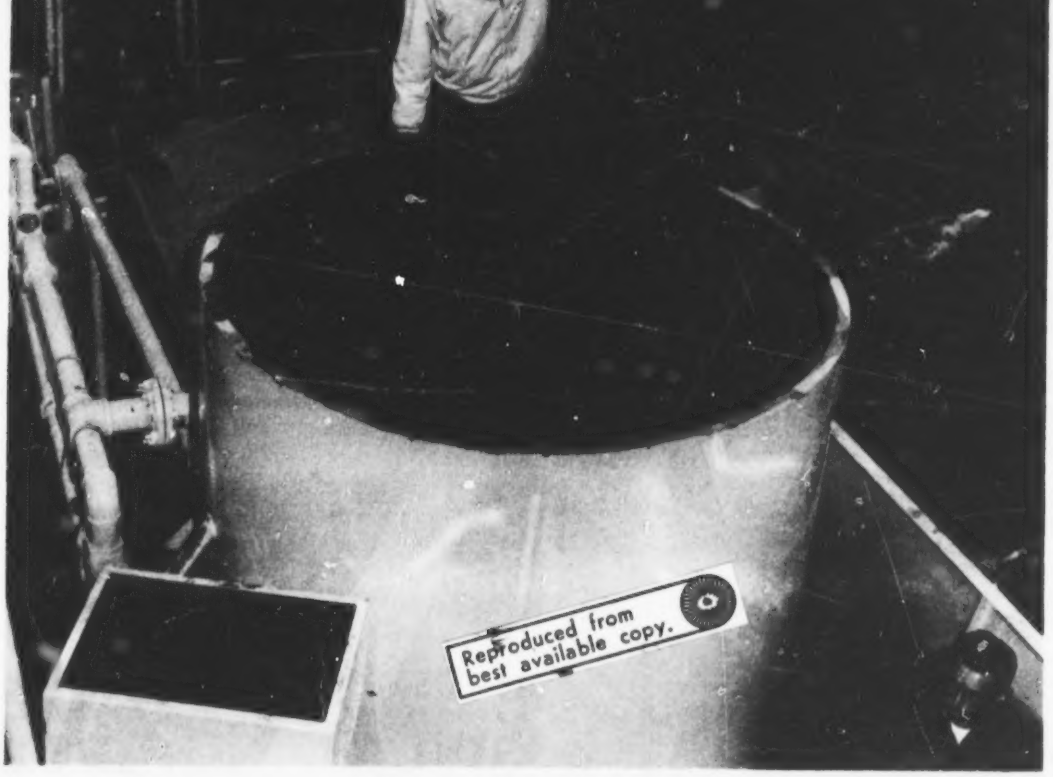

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Figure 38. Centrifuge Inlet Screen Installation in Surge Tank

SECTION VII

OIL/WATER CENTRIFUGE

DESCRIPTION

The oil/water centrifuge, mounted on the skimmmer deck as shown in Figure 2, was used to separate the oil/water emulsions collected in the surge tank on the skimmer barge. A centrifuge is ideally suited for separating substances of differing densities because it uses the centrifugal forces produced by rotational motion to create an intense gravitational field. The higher the rotational speed, the larger the gravity field, and hence the larger the force causing separation of the different density particles. The larger the separation force, the faster the separation of these particles takes place.

The oil/water centrifuge was designed for the present application and operated on a continuous basis utilizing an annulus-type centrifuge barrel. The annulus-type centrifuge barrel consists of two concentric cylinders that rotate as a single assembly, as shown in the simplified cross section of Figure 39.

As the oil/water mixture is pumped into the centrifuge the fluid encounters the end plate of the inner barrel. The end plate directs the mixture radially outward to the annulus where it flows axially to the discharge end of the centrifuge barrel. At the same time the flow is also rotating with the barrel. While traveling the length of the annulus, the oil/water mixture is subjected to the tremendous forces produced by the high rotational speed of the centrifuge barrel. These forces separate the two fluids before the fluids reach the discharge end of the barrel, then the two fluids are physically separated by the flow splitter. The oil flows radially inward between the flow splitter and the inner barrel. Water, which gravitates to the outside, flows outside of the flow splitter and then radially inward between the flow splitter and the outer barrel. The fluids are discharged along the axial centerline in separate concentric pipes.

For this type of centrifuge, control of the oil quality is accomplished by adjusting the back pressure at the oil outlet with a pressure regulator.

INITIAL DESIGN AND CONSTRUCTION

The oil/water centrifuge was designed to process oil/water emulsion at a rate of 500 gpm under a centrifugal force field 4000 times the normal gravitational force. The horizontal drum, which consisted of two closed concentric cylinders, was supported at each end by ball bearings and weighed 1800 lb dry. The drum was rotated by means of a belt drive from a 100-hp diesel engine, which also drove a 500-gpm centrifugal feed pump, a 7.4-cfm air compressor, and other minor accessories, making the separator a self-contained package. The entire package, including the drive, weighed 8000 lb and required approximately 64 sq ft of deck space.

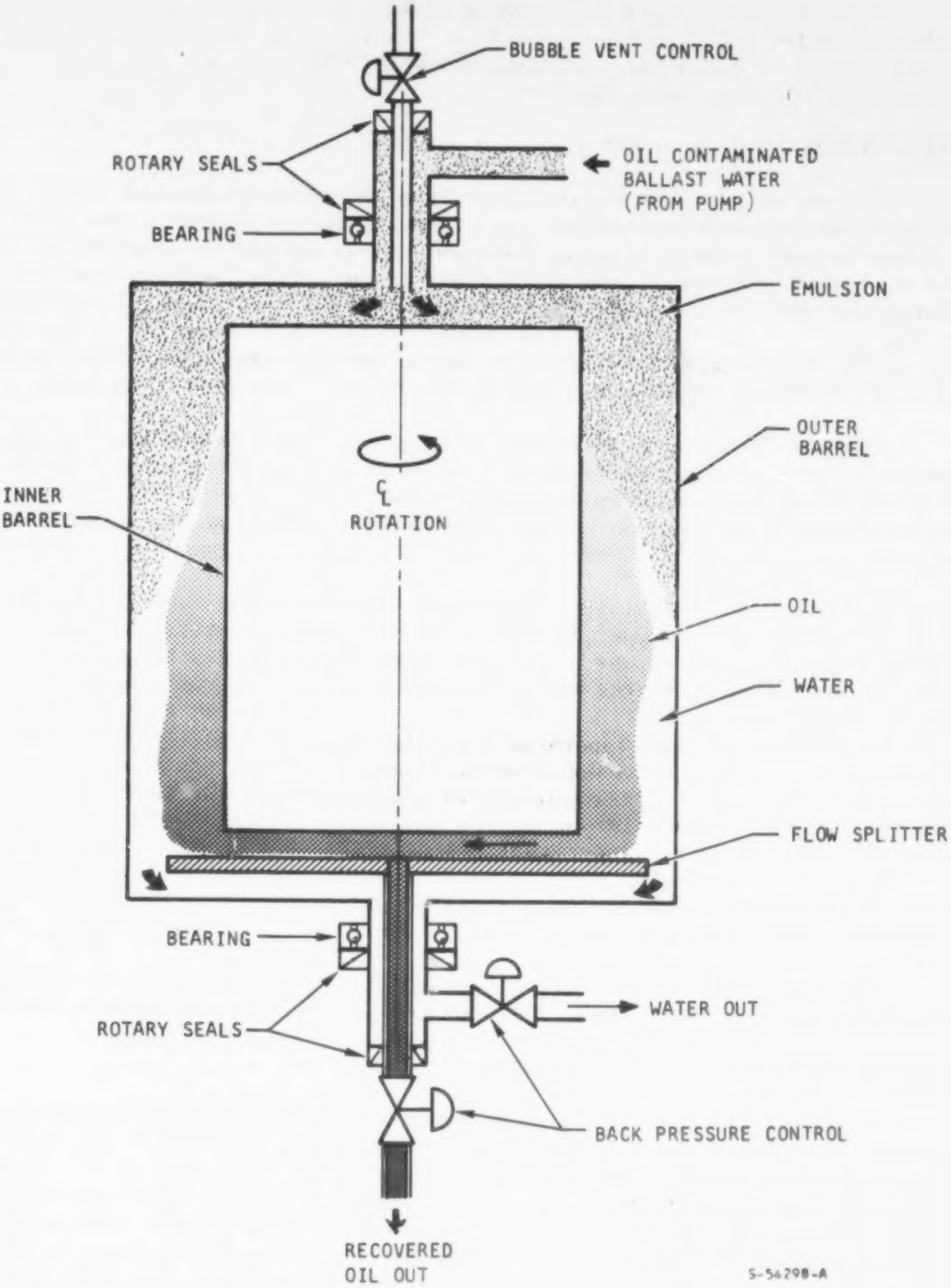

Figure 39. Cross Section of Oil/Water Centrifuge

When mounted aboard the skimmer barge, the centrifuge package admitted the oil/water emulsion through a 4-in. flanged pipe connection, and the clean water was discharged back into the quiet pond through a 6-in. pipe. The recovered oil was discharged into the oil reservoir through a 1-1/2-in. pipe.

PERFORMANCE TESTS OF CENTRIFUGE

Figure 40 shows the first version of the centrifuge, which was tested at the Signal Oil and Gas Company field laboratory in Huntington Beach. The test objective was to determine performance over a variety of conditions of flow rate, centrifuge speed, and inlet feed emulsion concentration to provide the basis for any required design improvements.

The test setup included instrumentation as shown schematically in Figure 41 and in the photographs in Figure 42.

A 4-in. line supplied the centrifuge with seawater from the Signal Oil and Gas Company water wells at a rate in excess of 500 gal/min. This water contained no oil, but it did contain a small amount of iron sulfide particulate matter that could be easily dissolved by addition of a small amount of hydrochloric acid. Oil was added to the seawater by pumping it from an open-top 15,000-gal Baker tank through a wobble-disk flowmeter and throttling valve system, and then into the seawater line downstream of the seawater turbine flowmeter. As an alternate the oil could be injected through the air bleed line that led directly into the centrifuge barrel. The air bleed line was located downstream of the feed pump and throttling valve.

After the oil was separated from the seawater, it was discharged from the centrifuge through a wobble-disk flowmeter into a sump. A floating weir reclaimed the oil from the surface of the sump and transferred it to a second 15,000-gal Baker tank. The seawater supernate was discharged from the centrifuge directly into a waste water sump.

During operation all fluid lines were instrumented for temperature, pressure, and flow monitoring, whereas the centrifuge was monitored through panel gages and additional temporary instrumentation. Panel instrumentation included inlet and outlet pressure on the centrifuge plus the oil discharge pressure for the centrifuge. In addition to the normal operating instruments for the engine, an oil mist pressure gage displayed the manifold pressure for the oil mist bearing lubrication system. In conjunction with the bearing lubrication system, a bearing temperature monitoring unit formed a part of the temporary instrumentation. This unit was a chromel-constantan thermocouple transducer that read out bearing temperatures directly in degrees Fahrenheit. Each bearing had one thermocouple placed adjacent to the outer bearing race and welded to the upper portion of each pillow block. The inlet bearing pillow block contained a total of two thermocouples; however, the second thermocouple was positioned to sense the outboard angular contact bearing.

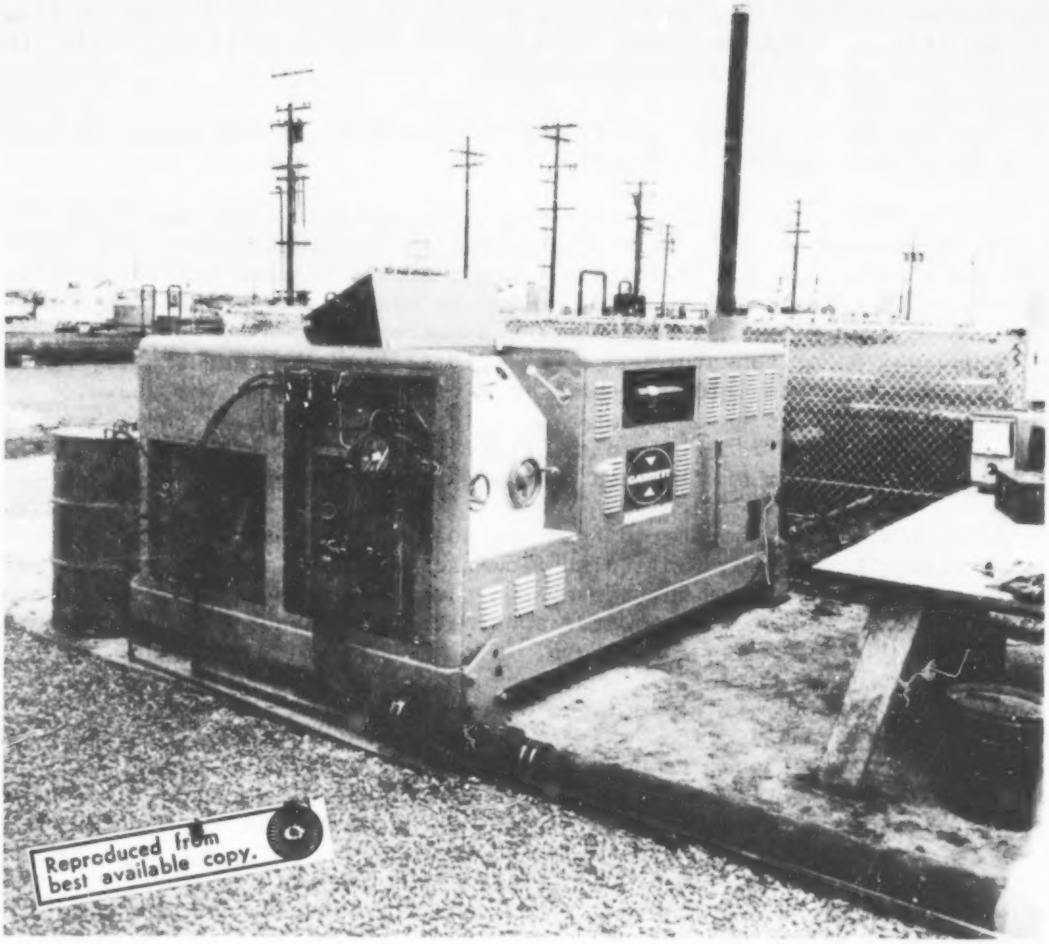

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Figure 40. Oil/Water Separator PN 585010-1-1

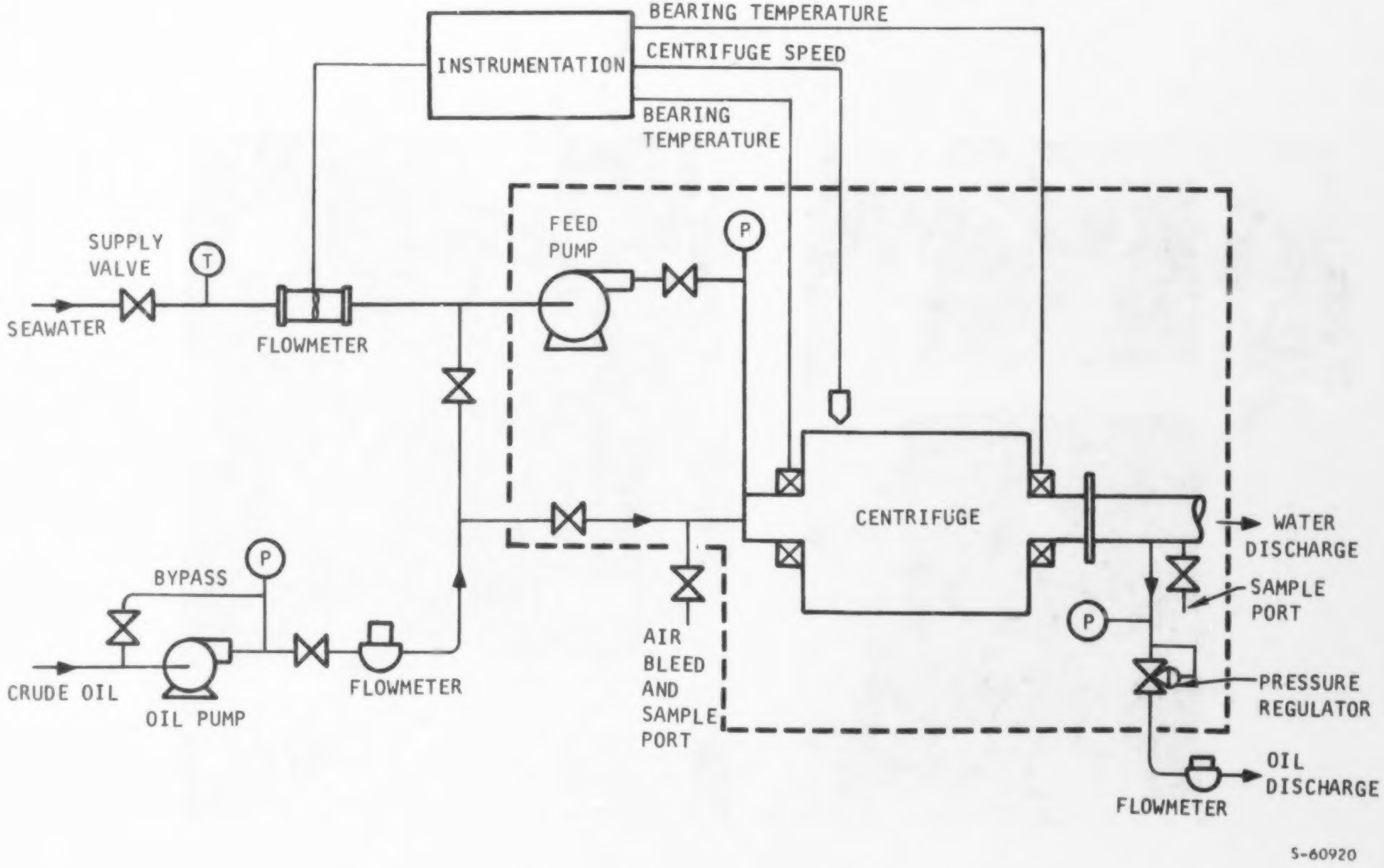

Figure 41. Schematic of Centrifuge Test Setup

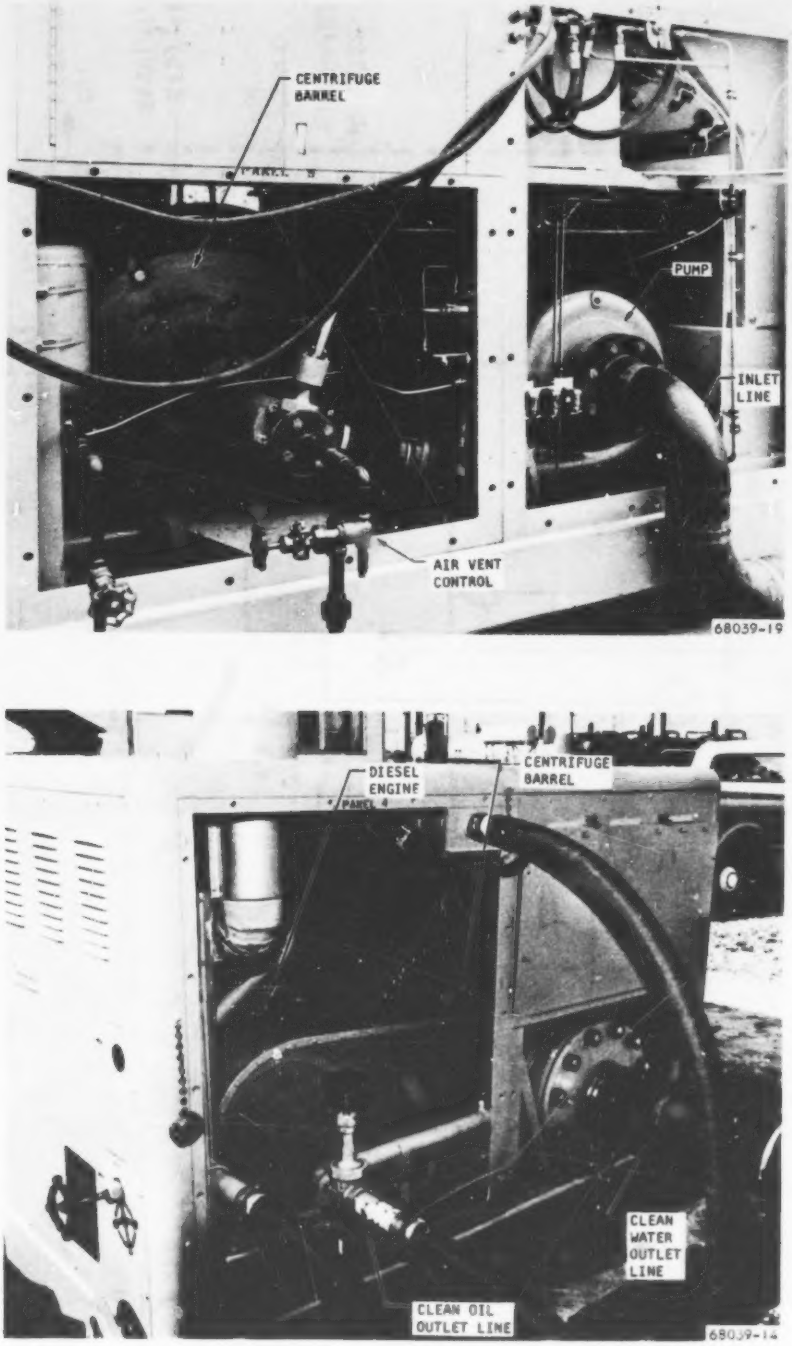

Figure 42. AiResearch Oil/Water Centrifuge

Centrifuge speed and seawater flow were sensed by magnetic pickups and displayed on a counter in Hertz. A simple conversion factor of 1.25 times the speed frequency gave the rpm of the centrifuge. A calibrated graph was required to convert the seawater flow frequency to gpm.

After completing the maintenance and startup procedures, a given set of conditions was selected for each test run. The seawater flow was adjusted to the preselected rate by first opening the supply line valve until 5 to 10 psi was recorded on the feed pump inlet pressure gage. Next the main pump discharge valve on the test panel was opened until the pump inlet pressure decreased to less than 1 psi. This procedure, which increased the flow rate of seawater through the pump, was performed in reverse order to decrease the flow rate. Parallel to seawater flow rate adjustment, the oil flow rate set point was established. A 50-psi pressure was arbitrarily established for the discharge from the oil supply pump and maintained through the test program. Most of the oil was bypassed through the centrifugal oil pump while a small percentage was drawn through a throttling valve, metered, then injected into the seawater line to form the test emulsion. The entire process took from 3 to 15 minutes depending upon the emulsion concentrations. Low oil concentrations took longer to establish than high ones. After the oil and seawater flow rates were established, a stabilization period of approximately 2 to 3 min passed before samples were taken.

Three seawater effluent samples were taken during a 3-min period using marked separatory funnels. After collecting three samples, an established volume of trichloroethylene was added to each. The oil was extracted from the water by the trichloroethylene, which was then drawn from the funnel, filtered, and colorimetrically measured. (See Appendix 2.) Contamination levels were expressed as parts by weight of oil per million of water.

DISCUSSION OF PERFORMANCE RESULTS

The centrifuge was placed into the field laboratory on March 2, 1970 and was subjected to a comprehensive performance test program. After a few tests were performed it became apparent that an insufficient oil discharge flow passage within the centrifuge was restricting the oil discharge. The oil level in the centrifuge was too high and was being carried over the discharge flow splitter with the clean water. On March 6, 1970, the centrifuge was disassembled in the field and a larger diameter flow splitter was installed. This modification was made to increase the oil discharge pressure and flow rate by increasing the pressure drop across the flow splitter. As the following test results indicate, however, a second more extensive modification was required to bring the unit up to its present performance level. Figures 43 through 45 display the performance of the originally designed unit.

Centrifuge speed as a function of engine speed is shown in Figure 43 with a second curve showing the point of minimum torque converter slip. Based on this curve the most economical operation speed would be 2,000 rpm for the drive system and 3,200 rpm for the centrifuge. This does not limit the centrifuge to 3,200 rpm; it merely points to the optimum power conversion for this sheave and drive system.

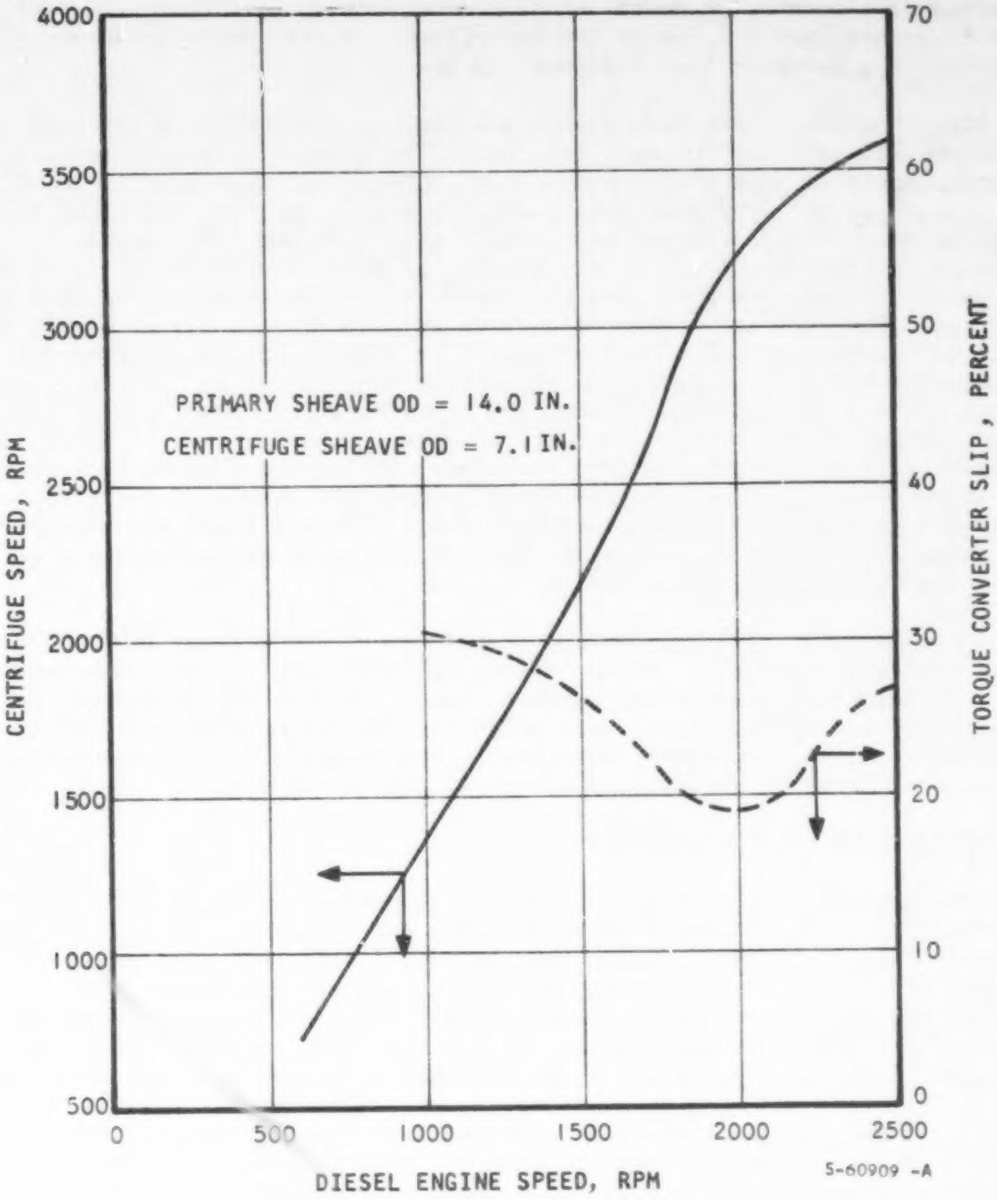

Figure 43. Centrifuge Speed and Torque Converter Slip

TEST DATE 3/18/70

AVERAGE CENTRIFUGE SPEED, 2750 RPM

INLET EMULSION CONCENTRATION 0.5 to 3.0 PERCENT OIL

LARGEST WEIR 585037-5

OIL GRAVITY = 21.5°API

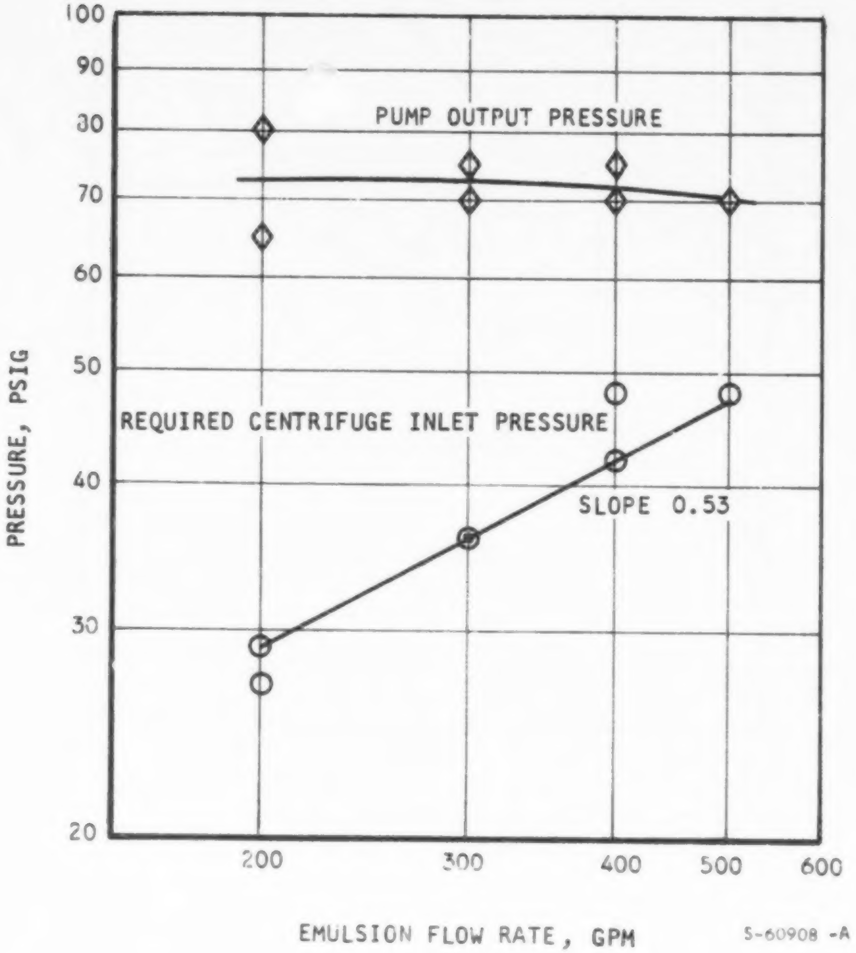

Figure 44. Pump Output Head and Separator Inlet Pressure Requirements

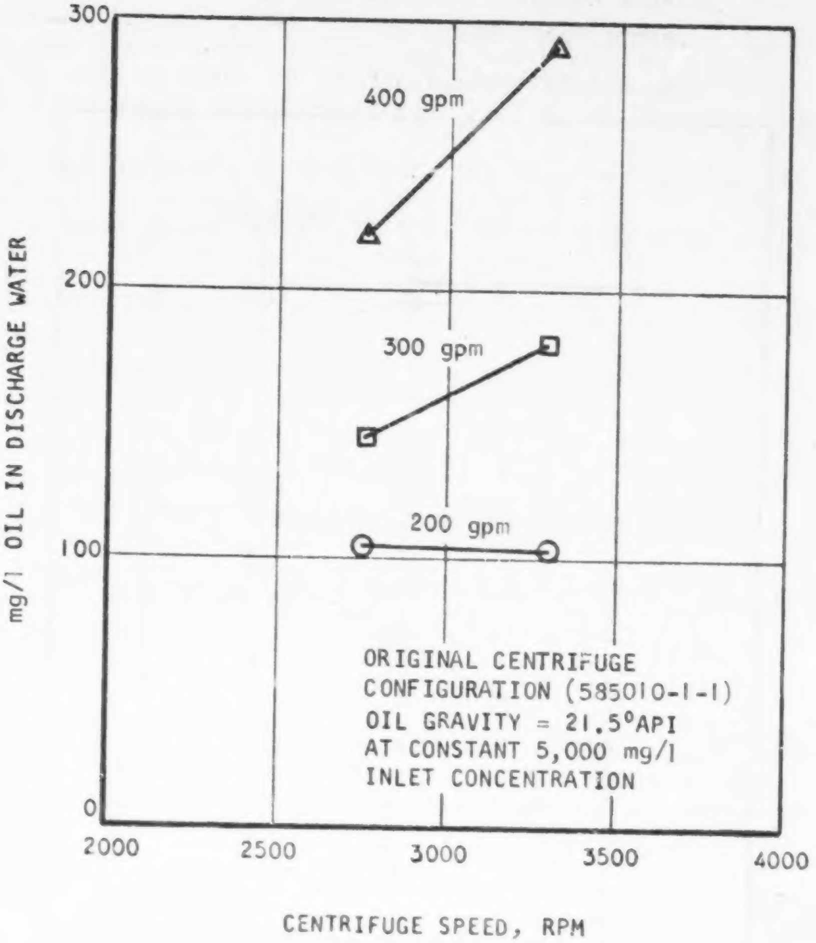

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Figure 45. Abnormal Centrifuge Performance

Figure 44 shows the pump output head and centrifuge inlet pressure as a function of the flow rate through the unit. The centrifuge feed pump, when driven at 1800 rpm, delivered an average pressure of 73 psig at flow rates from 200 to 500 gpm. The centrifuge inlet pressure requirement shown in this figure was well below the output of the pump and the throttling valve was used to drop the pump discharge pressure to meet the centrifuge inlet requirements. One of the most important facts obtained from this plot is that 500 gpm would flow through the centrifuge at less than 50 psi inlet pressure.

Figure 45 is a plot of the data taken with the original centrifuge. These data indicate that the centrifuge system does not provide the expected or calculated performance in that the unseparated oil increases as speed is increased. The basic equations governing gravitational forces within the centrifuge and the rate of particle settling within these force fields indicate that higher rotational speeds would give better separation if resident times were held constant. Inspection of Figure 45, however, revealed the opposite was true for the original unit. Better separation occurred at the 400-gpm flow rate when the lower centrifuge speed of 2750 rpm was used. Two possible explanations for this anomaly were considered and either one, or a combination of these, could have produced the measured results:

(a) Since the centrifugal feed pump was directly driven by the diesel engine, as was the centrifuge, it was not usually matched with flow rate requirements. Figure 44 shows this to be true by comparing the pump discharge pressure and centrifuge inlet pressure. The pump produced roughly twice the required head. The pressure head produced by the feed pump was created by restricting the throughflow with the throttling valve.

(b) When dissimilar fluids are passed through a restriction such as a partially opened valve, a mixing process occurs. Large droplets are broken into numerous small droplets, which are well mixed within the seawater.

The combination feed pump and throttling valve apparently created large numbers of small particles that were not being separated by the centrifuge. When the centrifuge speed was increased to effect a better separation, poorer separation occurred and more oil was discharged with the effluent water. Apparently the increased centrifugal speed could not overcome the detrimental effect of increased feed pump speed. The separating force was more than offset by the creation of the smaller droplets.

In Figure 46, quantitative data was taken at a constant centrifuge speed of 2750 rpm and the inlet emulsion was held constant at 5,000 mg/l oil in the seawater. At a water flow rate of 400 gpm the centrifuge discharge water contained approximately 200 mg/l oil when the oil was injected upstream of the feed pump. When the oil was injected at the air bleed line, which is downstream of the feed pump system, the discharge water contained approximately 120 mg/l oil. These results, plotted in Figure 46, indicate that a 50 percent decrease in the contamination level of the discharge water occurred when the oil was injected downstream of the pumping system.

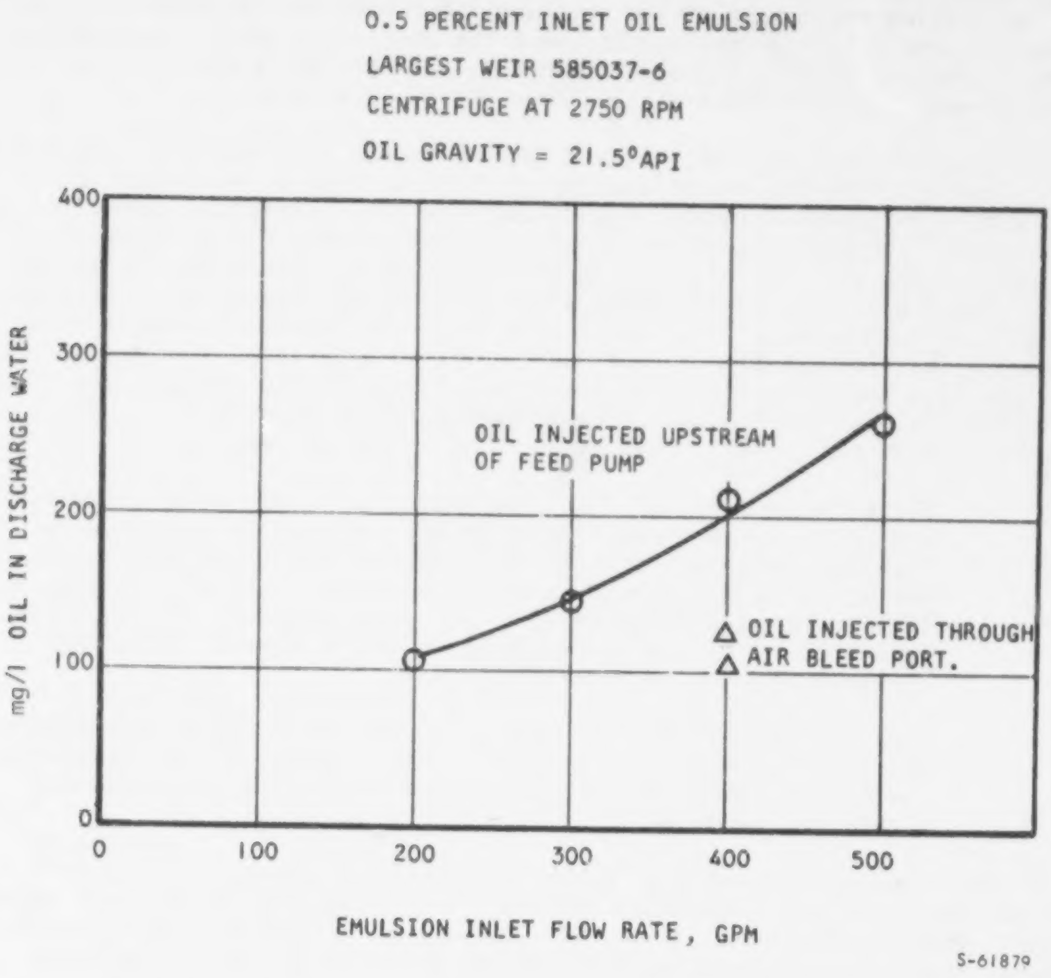

Figure 46. Crossplot of Original Performance Measurements

Based on the preceding data, it was concluded that one or more of the following decreased the separation efficiency of this unit:

(a) A turbulent flow pattern existed internally within the discharge section of the centrifuge, which disrupted the oil/water interface and carried oil over the weir

(b) The average oil droplet size in the feed emulsion was decreased by overspeeding the centrifugal feed pump, which created an emulsion that was more difficult to separate

(c) The throttling valve downstream of the feed pump becomes an emulsifying device

(d) High water flow rates create a flow pattern disturbance that may cause water to be carried with the oil down the 1/2-in.-diameter discharge tubes

DISASSEMBLY AND INSPECTION

The centrifuge was disassembled and inspected for obvious mechanical failures, and two separate problems were found. First, the carbon face seal at the inlet end was found filled with fine sand, which rendered it mechanically inoperable and caused it to leak. The same type seal was used on the outlet and although it had been leaking during the performance tests it was not filled with sand. The distortion of the mating surfaces caused by the drive torque on the outlet end was believed to have caused the leakage witnessed during operation. The carbon face seals on the inlet and outlet should be changed, or their installation improved, to stop the leakage flow.

The second problem area was corrosion, which also affected the seals as well as the pump vanes, end caps, turbine vanes, and the inlet and outlet housings. Figure 47 shows a corrosion pattern developing in the end cap. Figure 48, a photograph taken of this same part just prior to the design modification, shows that all surfaces exposed to the moving seawater were corroding more rapidly than the stagnant areas found between the turbine vanes. Figure 49 shows a closeup view of a turbine vane in which all surfaces were beginning to corrode, and Figure 50, an inside view of the discharge housing, reveals the blister type corrosion that had developed during exposure to seawater.

As a result of the conclusions reached after testing and disassembly, the following recommendations were made:

(a) The internal weir should be redesigned to allow a 360-deg flow on the oil discharge side. The original configuration involved eight separate 1/2-in tubes. The preliminary tests indicated that the pressure drop and turbulence associated with this design is excessive. Also, the downstream oil discharge plumbing was enlarged to decrease the pressure drop and reduce the possibility of plugging.

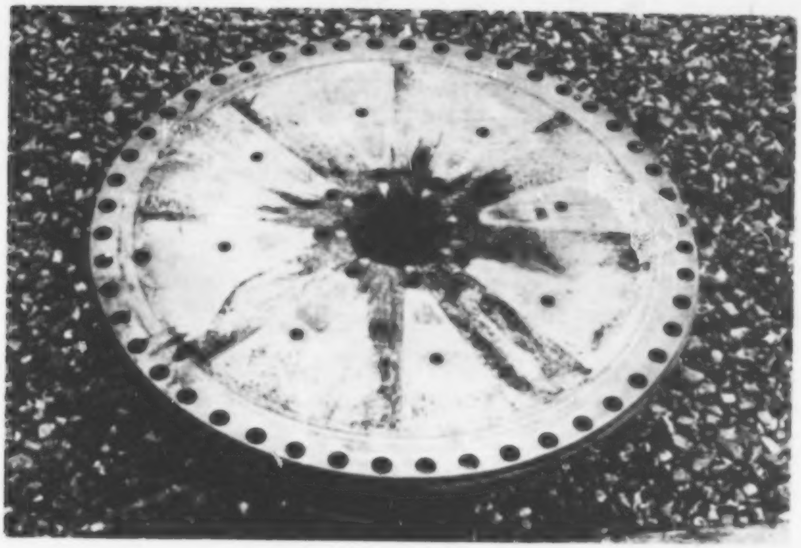

Figure 47. End Cap Seawater Corrosion (March 6, 1970)

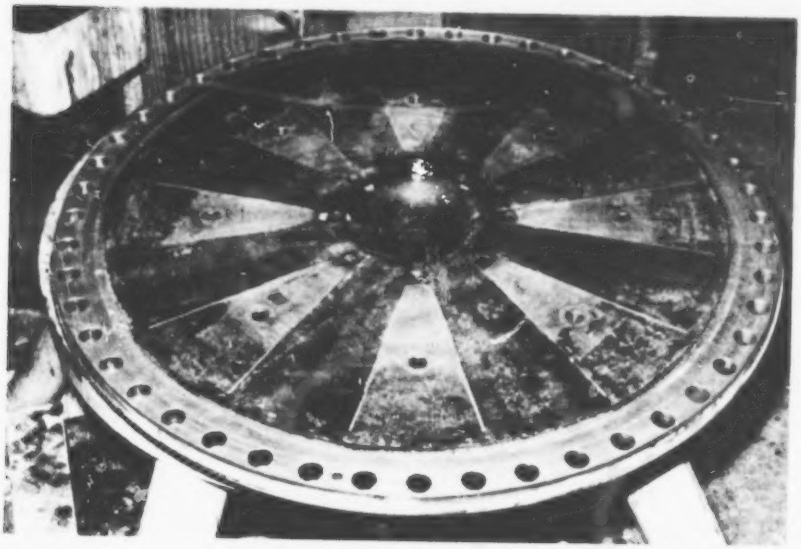

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Figure 48. End Cap Seawater Corrosion (March 27, 1970)

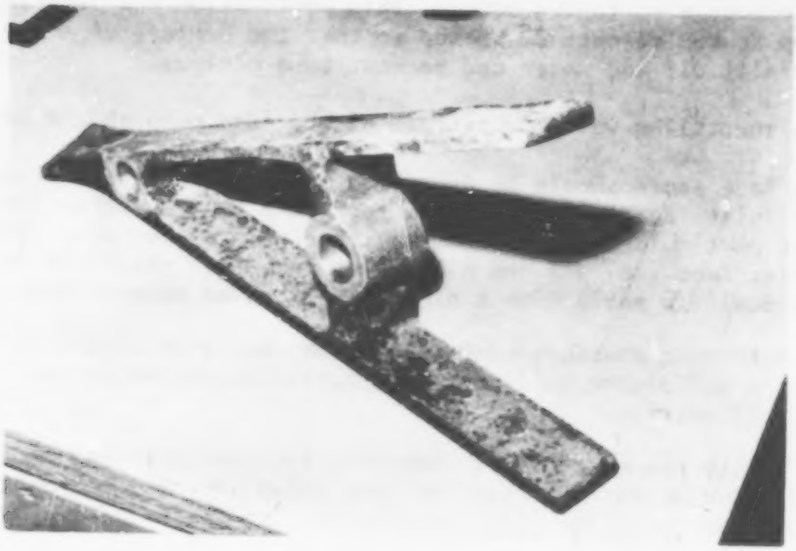

Figure 49. Corroded Discharge Vane, PN 585014

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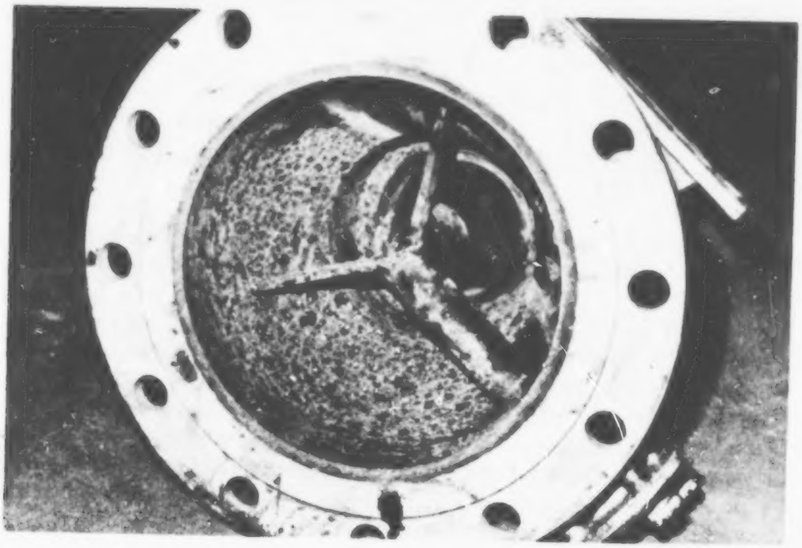


Figure 50. Corroded Discharge Housing, PN 585024

(b) The feed pump should be disengaged from the diesel drive and be driven by a varidrive motor. This would allow the centrifuge pump to run at optimum speed, so that the degrees of emulsification of inlet oil and water can be kept to a minimum.

(c) The throttling valve downstream of the feed pump should be removed.

(d) The face seals should be protected from particulate contamination. The inlet face seal should incorporate a flow diverter that would prevent particulate matter from backing up into the seal. Both the water outlet face seal and the oil outlet face seal should be replaced by the dual lip seals with a bleed line located between them.

(e) An automatic pressure-controlled flow regulator should be installed on the oil discharge line. This minimizes the water content in the oil outflow.

The centrifuge was modified to incorporate recommendations made in (a) and (e); the other recommendations required more extensive design changes and were not incorporated at this time.

DESCRIPTION OF THE DESIGN MODIFICATIONS

Cross sections of the original and modified designs are shown in Figure 51, with all modified parts shaded in the lower view; individual components are shown in Figures 52 through 55. These components were painted with one of three epoxy type corrosion-preventive compounds specifically formulated for seawater environments.

Figure 52 shows an overall and closeup view of the inlet pump vanes as they were installed onto the internal drum. These vanes were coated with a corrosion-preventive epoxy type paint manufactured by Amercoat Corporation and designated as No. 93/84.

The end cap surfaces shown in Figure 53 have been cleaned and painted with Mogna Coatings protective primer and topcoat No. 4-G-14-4 and 4-W-1-4.

Figures 54 and 55 show two views of the redesigned flow splitter. Figure 54 is an overall view of the flow splitter, which has been painted with Product Techniques PT750 corrosion-preventive compound. The stainless steel oil discharge tube was assembled into the flow splitter and the final configuration is shown in Figure 54. Figure 55 shows the flow splitter without the oil discharge tube mounted onto the internal drum. Close inspection of the center port shown in this view reveals the 1/4-in.-wide oil flow passages between the flow splitter and internal drum.

Figure 56 is a photograph of the automatic oil discharge control system. A bypass line was included in this system for testing purpose and is shown bridging the pressure regulator. Three ball valves in this system provide independent selection of either regulated or bypassed flow control. The sampling port at the base of the regulator was used to obtain some of the oil samples.

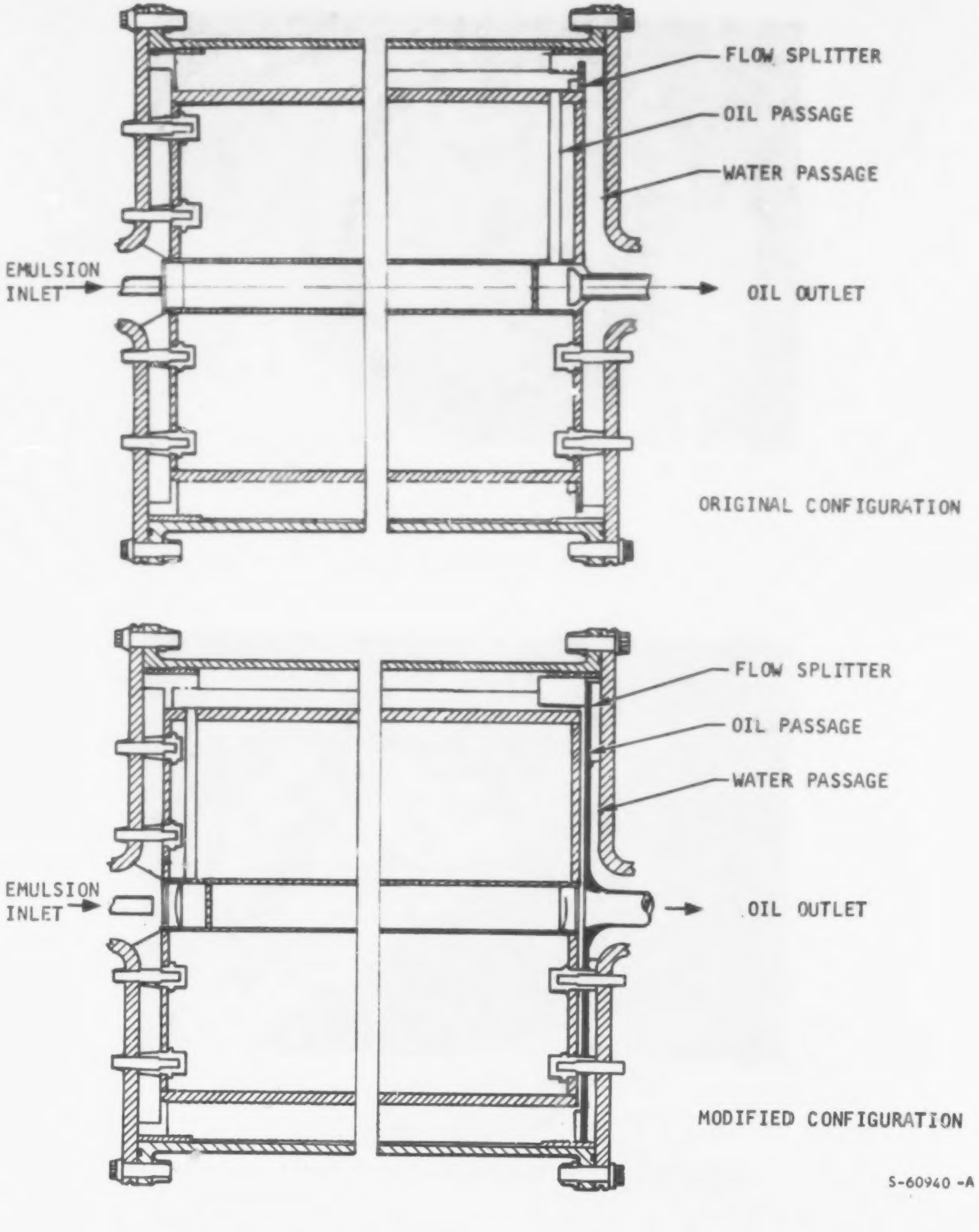
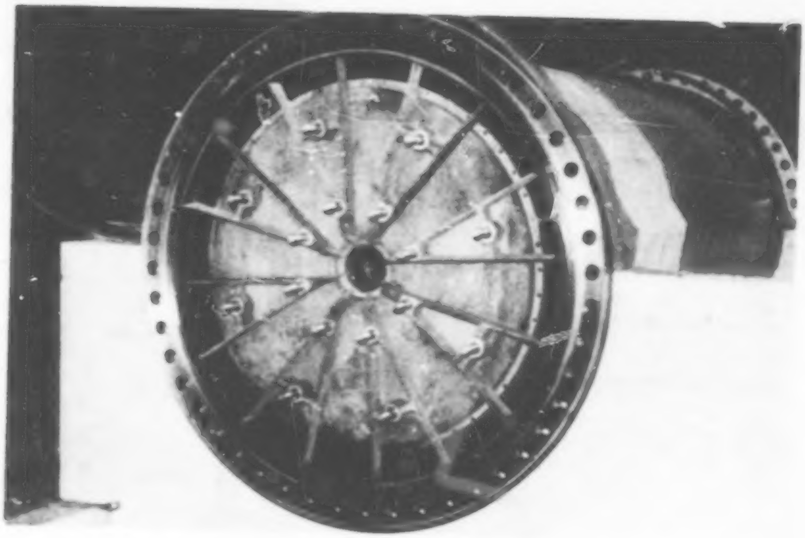


Figure 51. Cross Section of Original and Modified Design



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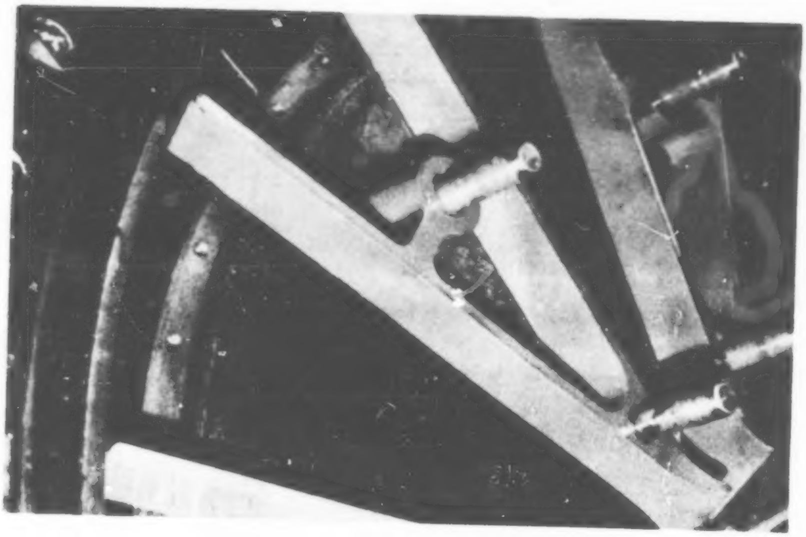
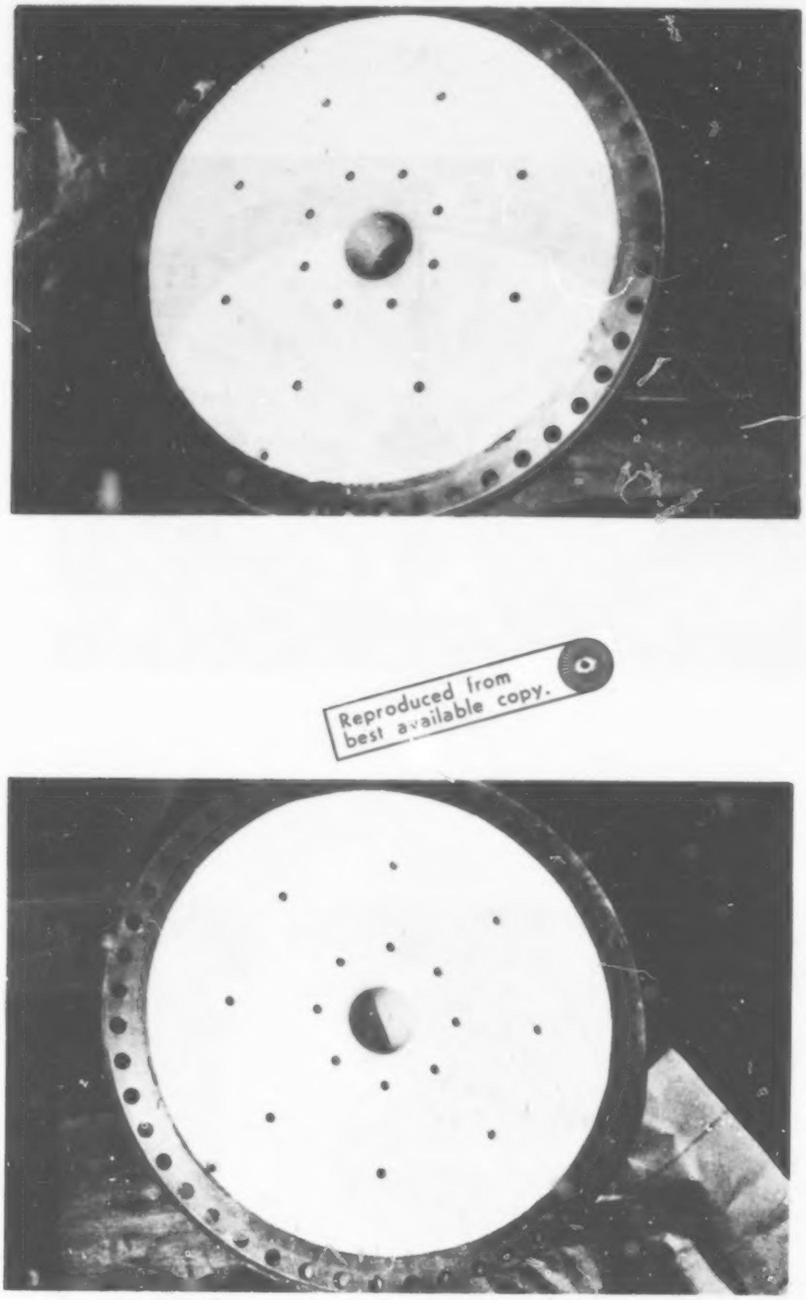


Figure 52. Inlet Configuration of Modified Centrifuge



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OUTLET END CAP

Figure 53. Corrosion Protection for End Cap Surfaces

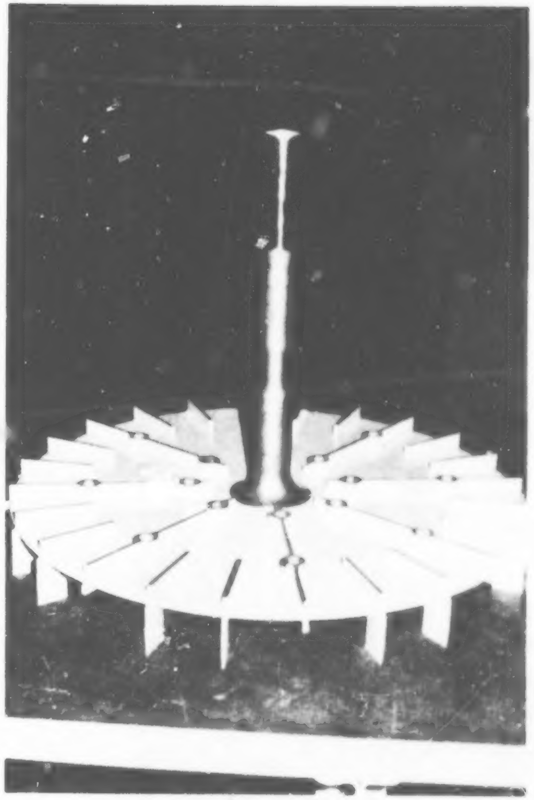

Figure 54. Outlet Flow Splitter and Oil Discharge Tube Assembly

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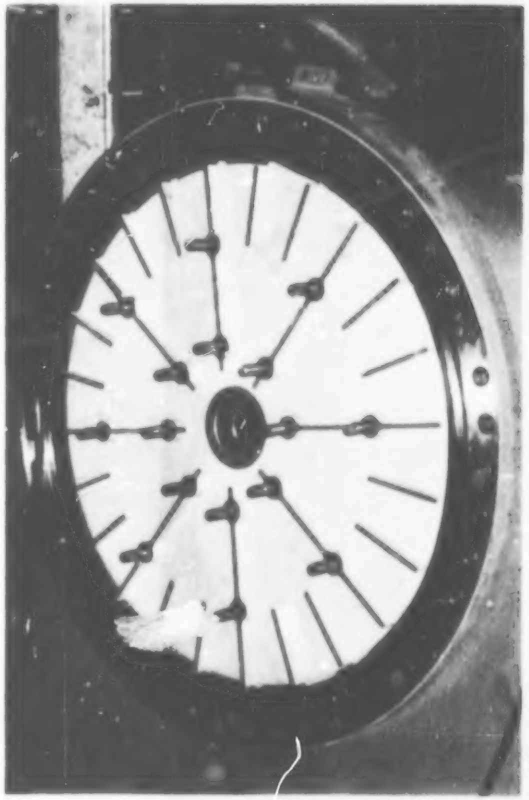

Figure 55. Outlet Flow Splitter and Drum Assembly

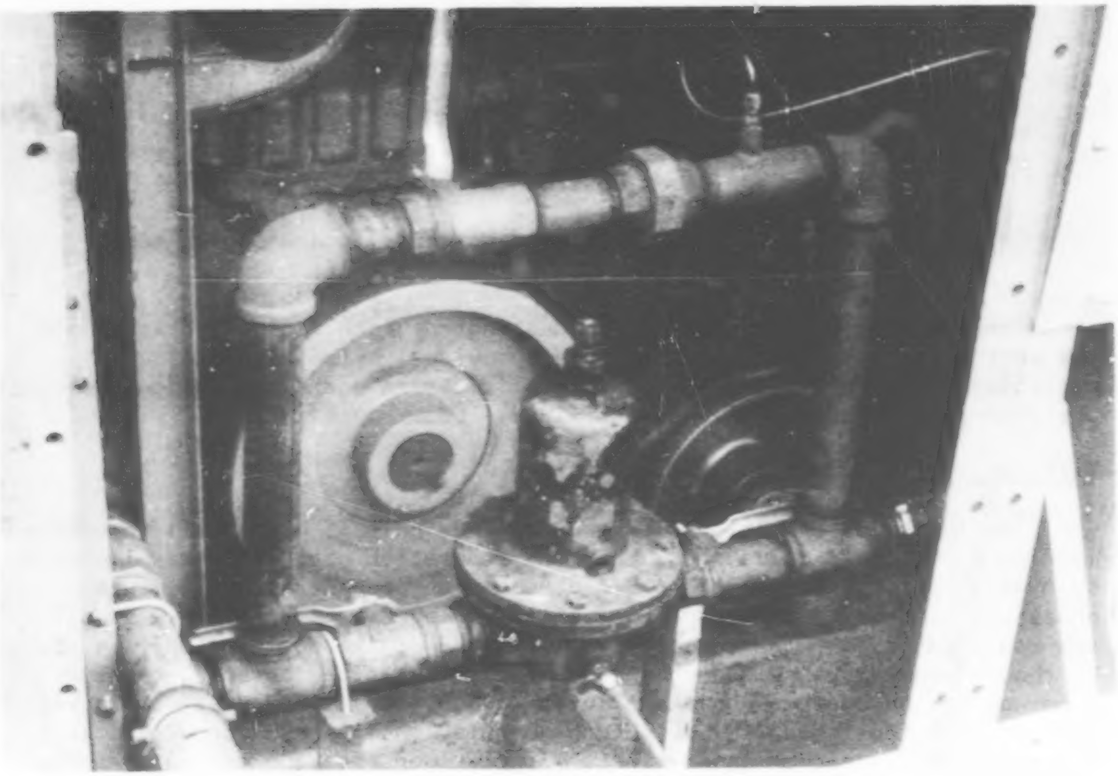

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Figure 56. Oil Discharge Pressure Regulator

PERFORMANCE TEST OF MODIFIED CENTRIFUGE

A new test program with the following objectives was performed with the reworked centrifuge during May and June of 1970.

(a) Define the separator performance characteristics

(b) Check the mechanical and functional centrifuge characteristics during operation with warm emulsions (120-160°F)

(c) Investigate the effect of solid particles on separation ability and determine their distribution within the centrifugation system

(d) Determine the feasibility of increasing the separation efficiency by injecting additives upstream of the centrifuge

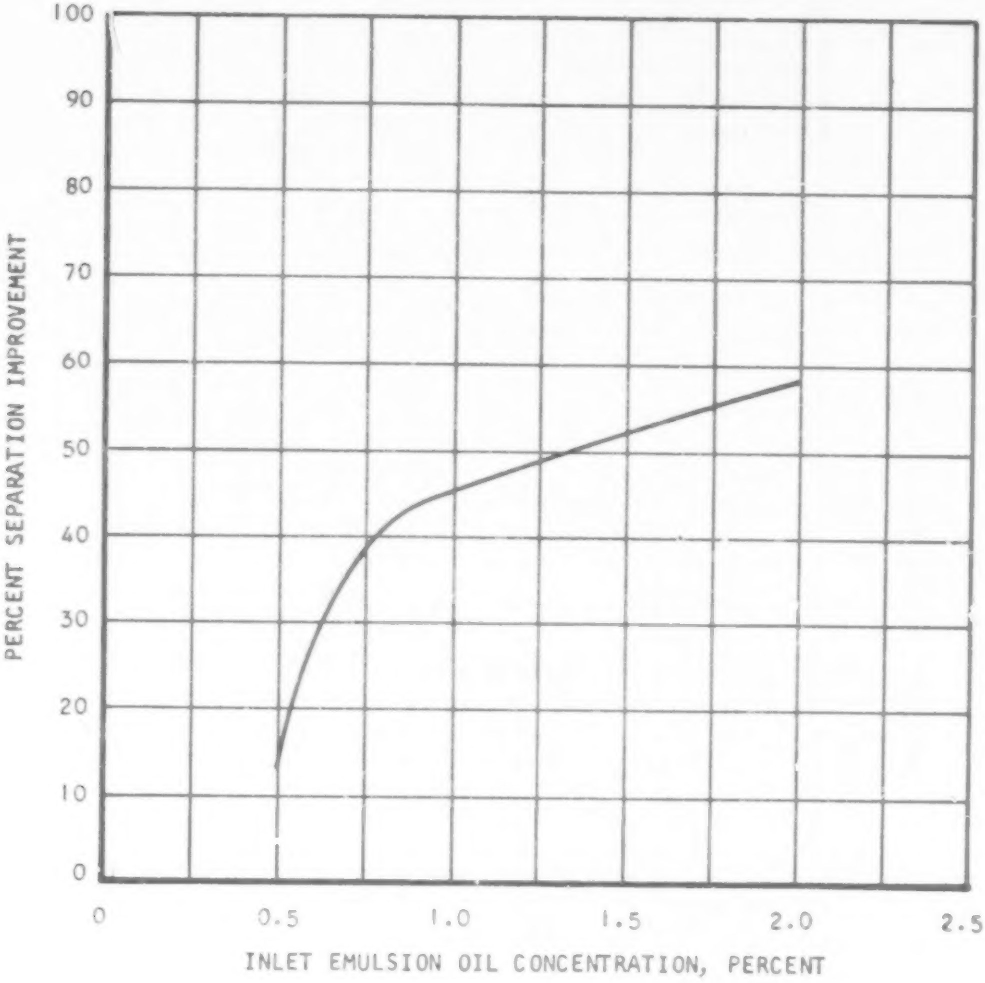
(e) Determine whether a multiple-stage centrifuge would be more efficient

The tests were conducted at the Huntington Beach field laboratory and the test setup was similar to that used previously (see Figure 41). A particle counter was used to measure particle size and distribution at points upstream and downstream of the centrifuge. (See Appendix 3.)

Test Results

The improved separation with the modified unit is graphically presented in Figure 57. This curve shows that the separation capability was improved by over 50 percent at the higher inlet emulsion concentrations. It was necessary to sacrifice a portion of the flow capacity in order to install the modified parts. The reduced flow capacity of the modified unit is caused by the increased pressure drop show in Figure 58. The increased pressure drop was caused by the unbalanced inlet and outlet pump-turbine configuration. As originally designed, the pump-turbine relationship was hydrodynamically balanced and functioned as an effective power conservation mechanism. The power consumption for the modified unit remained low, however, as shown in Figure 59.

Figure 60 confirms increased separation with increase in centrifuge speed, as would be expected from centrifugal theory. This curve is a plot of the oil concentration in the discharge water (mg/l) vs centrifuge speed for a constant inlet flow rate of 200 gpm. The inlet emulsion contained 10,000 mg/l oil of 21 to 25° API gravity. The results showed a vast improvement over the original unit for which the separation ability decreased with speed, as shown in Figure 60. This phenomenon was due primarily to the emulsifying effect of the feed pump on the original unit, since that pump was directly connected to the engine driving the centrifuge. The resultant excess flow required a throttle valve between the feed pump and the centrifuge.



PERCENT SEPARATION IMPROVEMENT = $100 \left(1 - \frac{A}{B}\right)$

A = mg/l OIL IN DISCHARGE WATER FOR MODIFIED CONFIGURATION (PN 585010-1-3)

B = mg/l OIL IN DISCHARGE WATER FOR ORIGINAL CONFIGURATION (PN 585010-1-1)

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Figure 57. Performance Improvement

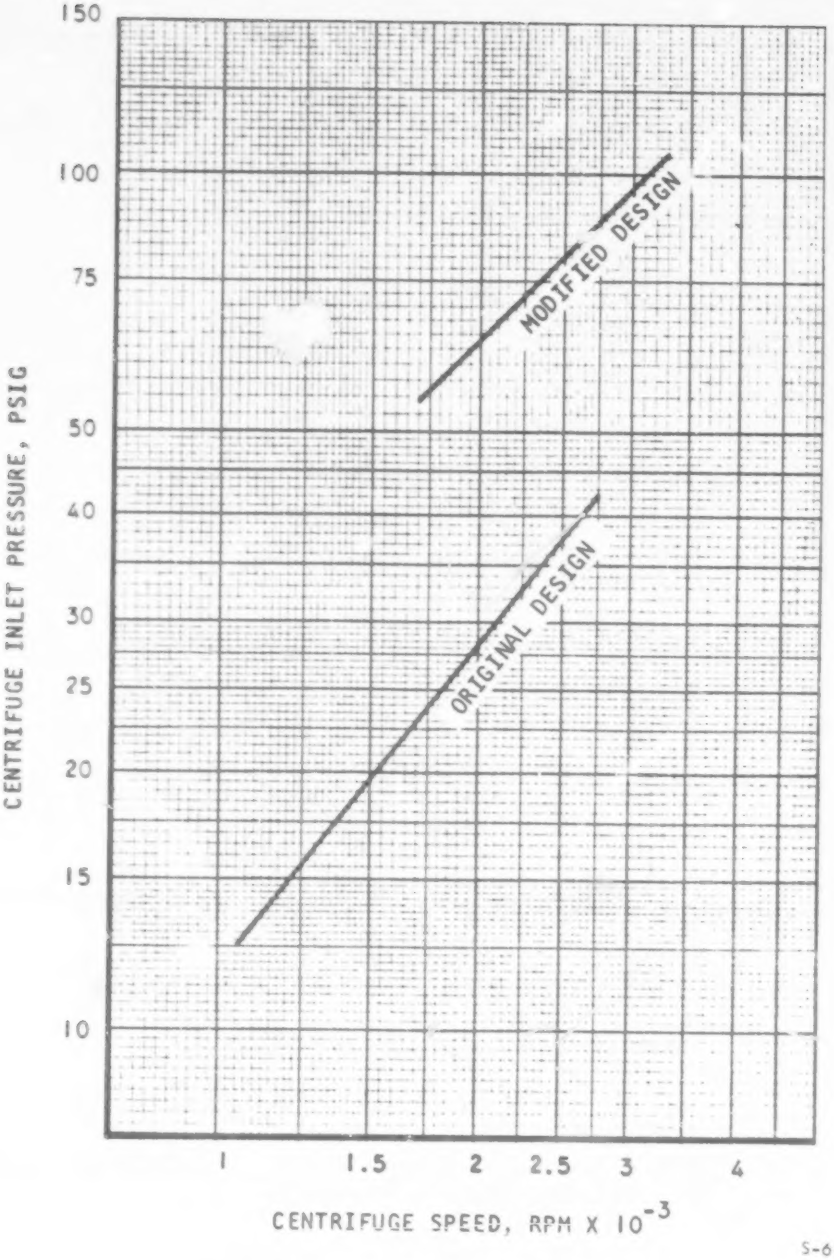

Figure 58. Oil/Water Separator Inlet Pressures

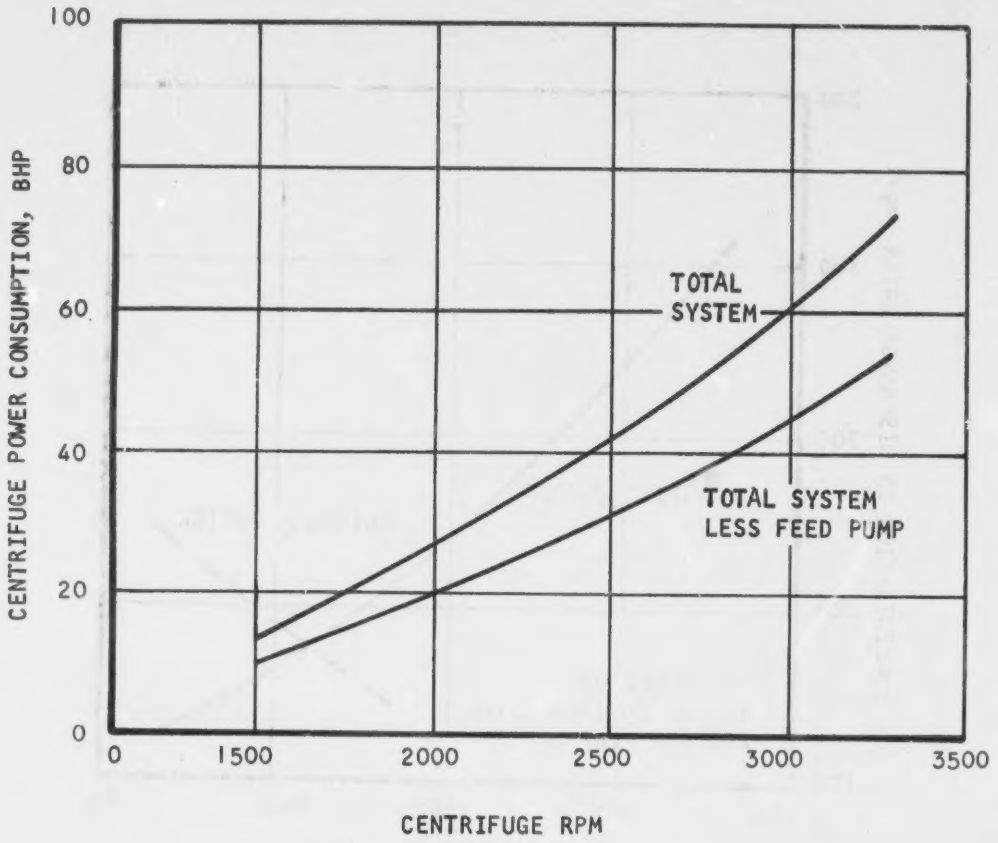

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Figure 59. Preliminary Centrifuge Power Requirements (Steady-State)

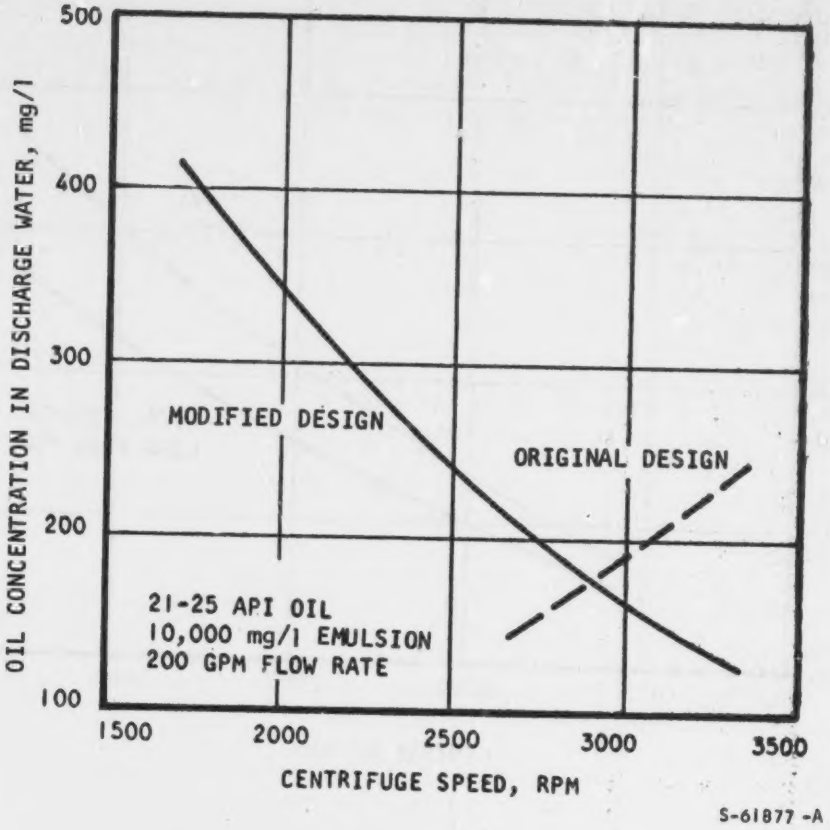

Figure 60. Variable Speed Performance

The performance plot of the modified centrifuge is shown in Figure 61. This figure shows the oil concentration in the discharge water as a function of inlet emulsion concentration for inlet flow rates of 100, 200, and 300 gpm at a centrifuge speed of 2750 rpm. The oil concentration in the discharge should be and was reduced at higher speed, as shown in Figure 60.

The effect of improved separation with emulsions containing oil of higher API gravity (lower specific gravity) is shown in Figure 62. The unit was operated at 2750 rpm with constant inlet flow rates of 200 gpm. Two oils of different API gravity were used to derive these curves. This plot confirms that the unit will separate lower density oils more easily than higher density oils, as would be expected from theory.

Two methods of increasing the separation efficiency were demonstrated. The first method was to inject an emulsion breaker (coagulant) into the feed emulsion. The emulsion breaker, Tretolite JN9045,* was injected into the feed emulsion at a rate of fifty parts emulsion breaker per million parts of emulsion and the separation efficiency was increased approximately fifty percent as shown in Figure 63.

An increase in separation efficiency resulted when oil added to 140°F waste water effluent from the skim tank was processed through the centrifuge. When compared to the measured ambient performance (68°F) of equivalent flow, speed, and oil gravity, an increase of 260 percent was obtained with the warm waste water as shown in Figure 64. It is difficult to predict the centrifuge performance for lower inlet temperatures since the hydrodynamics of this unit would be affected.

Figure 65 reveals the distribution of oil-free solids within the processing system. The oil-free solids include all of the filterable solids within the source water and include organic as well as inorganic material. Organic material, when heated in the presence of air, is reduced to gaseous products leaving behind only inorganic material, which is defined as "ashed solids" in Figure 65. These data show that the solids are removed from the processed fluids and that the discharge water from the centrifuge approaches the quality required for reprocessing back into the well formation. This process would eliminate, or greatly reduce, the amount of environmental-polluting waste water discharged into coastal waters or other common waste dumps.

A general summary of all the performance data gathered on the modified unit is presented in Figure 66. This figure shows the oil concentration in the discharge water vs the oil concentration in the inlet emulsion for a range of flows from 100 gpm at maximum test speed to 500 gpm at minimum test speed.

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*Tretolite, a division of Petrolite, Inc., St. Louis, Mo.

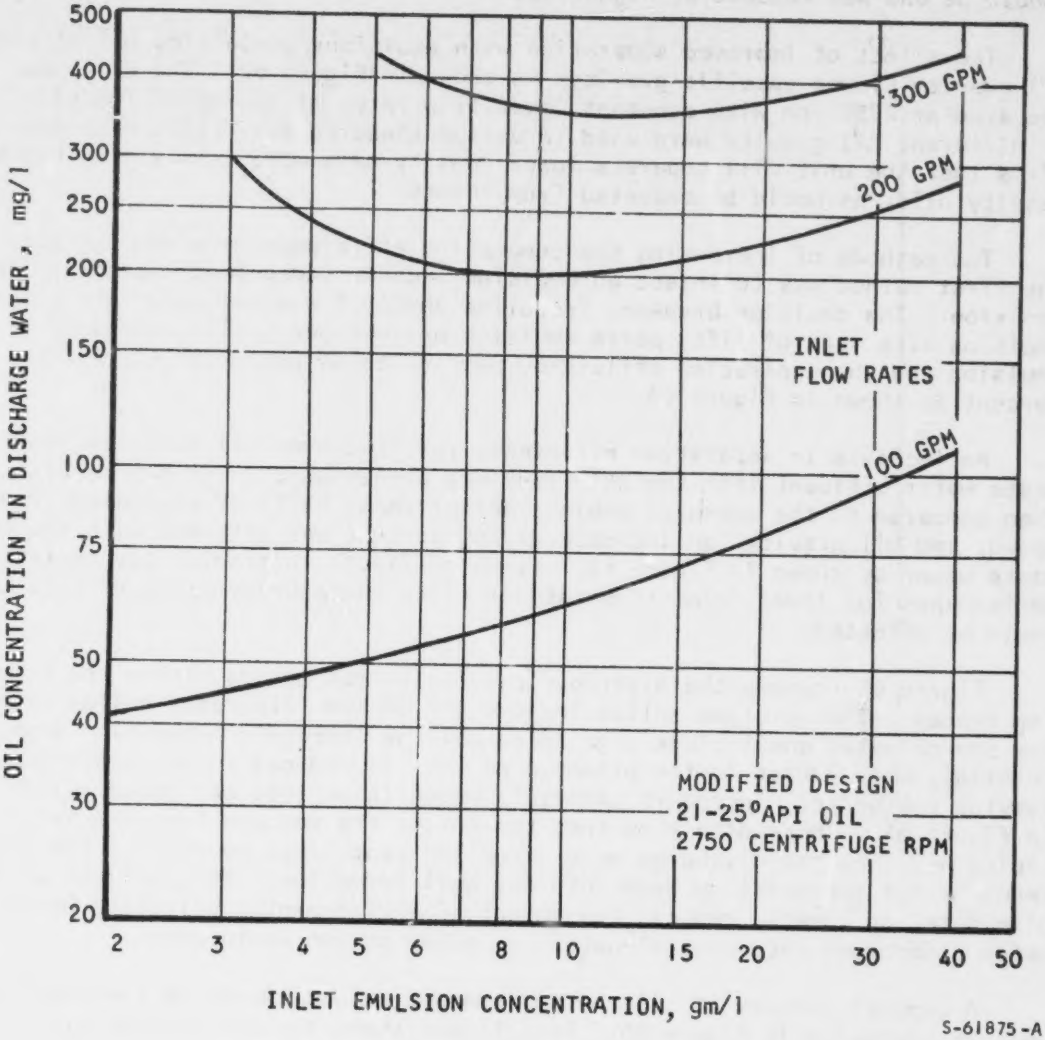

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Figure 61. Detailed Performance Plot at Reduced Centrifuge Speed

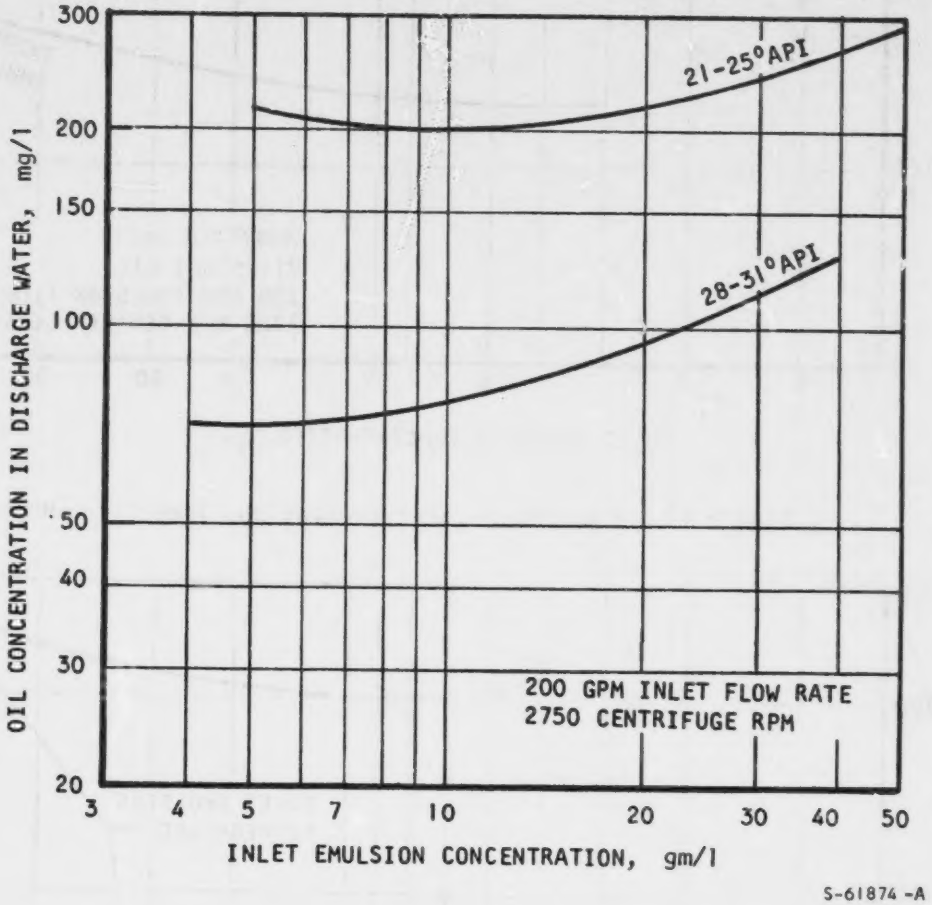

Figure 62. Separation as a Function of Oil API Gravity

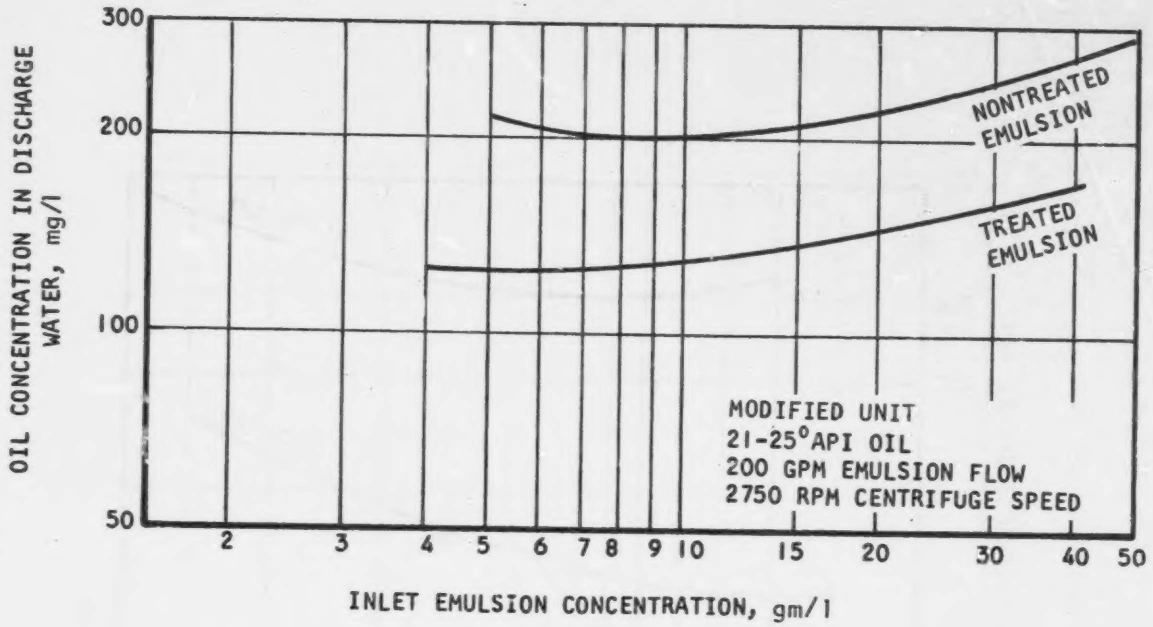

Figure 63. Emulsion Breaker Evaluation, Tretolite JN9045

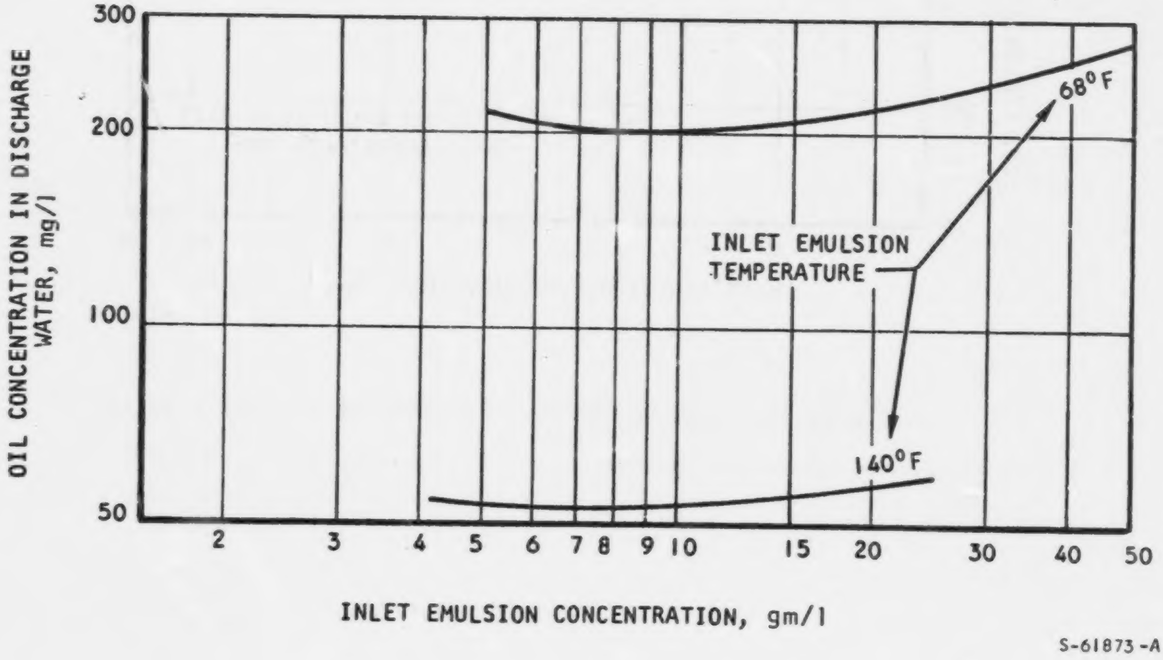

Figure 64. Influence on Separation by Increased Temperatures

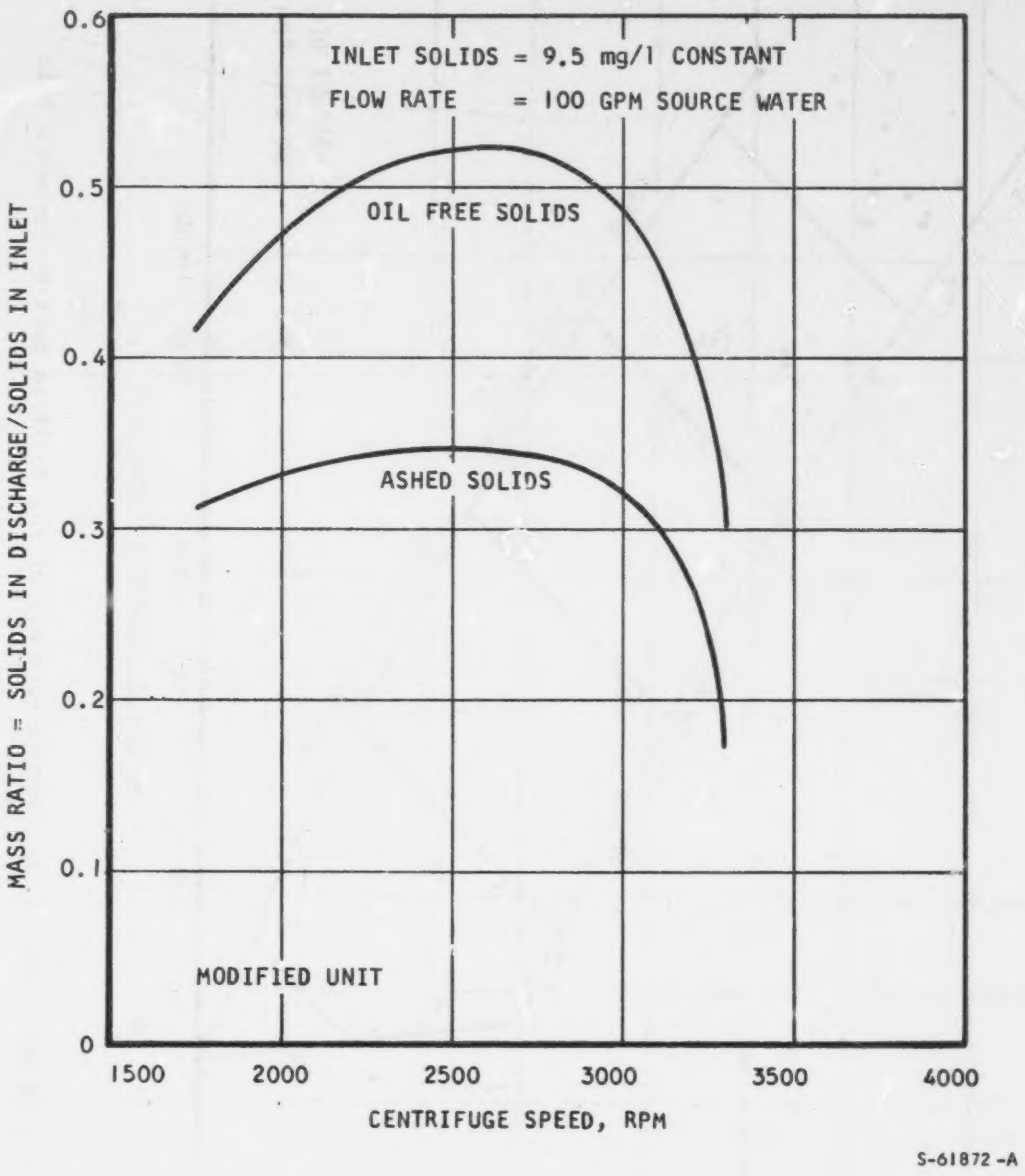

Figure 65. Solids Distribution within Centrifugation System

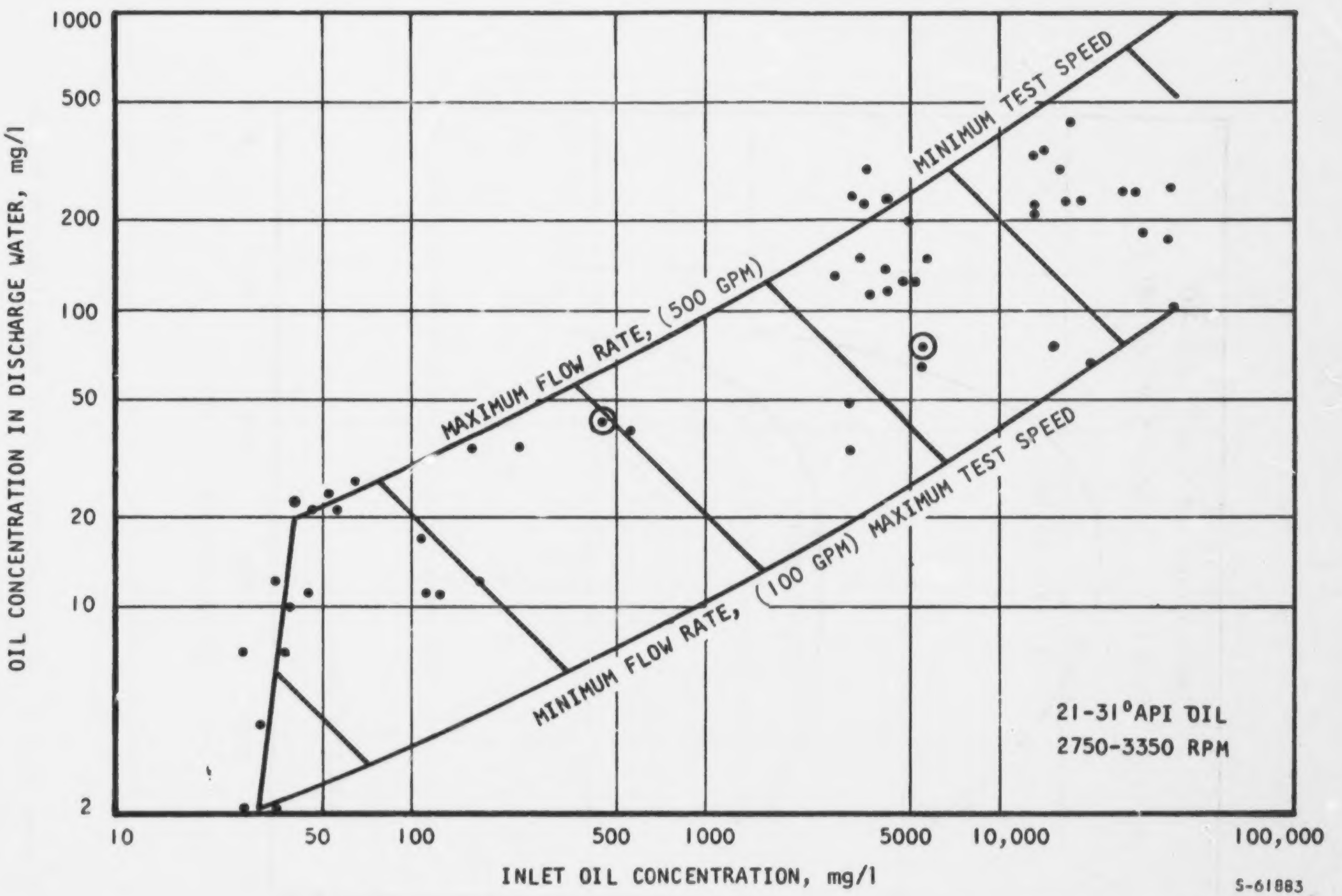

Figure 66. General Map Representing All of the Modified Unit Performance Data

This plot also provides the necessary information required to deduce the performance of two centrifuge units in series or a two-stage centrifuge. By selecting a starting emulsion of 10,000-ppm oil and using the 500-gpm data curve, the outlet from the first unit would contain approximately 390 mg/l oil. When this concentration is used for the inlet of the second unit, its outlet concentration would be 58 mg/l oil. This indicates that series units or a multiple-stage unit would be more efficient than a single unit. Data contained within Appendix 3 also confirms this analysis of Figure 66.

In order to determine the effect of multistaging the centrifuge, or operating two centrifuges in series, the effluent from a series of test runs was collected in a vacuum truck. The data from these runs is shown as the first nine runs of data page 5 of 5, Data Group 6, of Appendix 3. This liquid was then withdrawn from the vacuum truck and rerun through the centrifuge, with the results shown in runs 10 through 13 on the same data sheet.

SECTION VIII

SYSTEM TESTING

Skimmer barge testing at sea was conducted off the coast near Santa Barbara California by General Marine Transport of Santa Barbara, Inc. under the direct supervision of AiResearch. (The General Marine Transport Company was intimately involved in the cleanup of the notorious oil leak at Santa Barbara in February of 1969.) These tests were part of the Sea Dragon test program conducted by AiResearch under contract for the American Petroleum Institute. The EPA permitted the skimmer barge and centrifuge to be part of the Sea Dragon test equipment, which is a total containment and oil spill recovery system. In addition to the skimmer barge and centrifuge, Sea Dragon test equipment included oil containment/sweeping booms used to funnel the surface oil into the skimmer barge and an inflatable oil storage receiver for the recovered oil. AiResearch Report 70-6787 describes the Sea Dragon tests and was concerned mainly with the evaluation of the booms. The skimmer barge was tested for the collection of oil with and without the use of the boom.

The objectives for the skimmer tests were:

(a) To check seaworthiness under various sea conditions

(b) To determine towing forces

(c) To determine the skimmer efficiency

(d) To evaluate the paddle wheel for skimming improvements

DESCRIPTION OF EQUIPMENT USED FOR SEA TESTS

Units Under Test

(a) Skimmer barge (see Section VI for description)

(b) Centrifuge installed on the skimmer barge (see Section VII for description)

Vessels Employed

The following General Marine Vessels were used for towing, boom deployment, and transferring personnel.

(a) Sea Truck--65- by 23-ft supply boat powered by two 400-hp diesel engines. This was the the principal boat used in the program for moving the skimmer to the test site and for towing the skimmer, with or without booms.

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(b) Packer--65- by 21-ft supply boat, powered by two 300-hp diesel engines. This vessel was used for boom deployment and boom towing when two boats were required.

Other smaller boats were used for boom deployment, personnel transfer, lighter towing jobs, and other tasks.

It should be noted that only approximately 100 hp is needed for towing while skimming oil, but 600- to 800-hp vessels are required to move the skimmer rapidly from one site to another.

Booms

The description of the booms follows:

(a) Rapidly Deployable Boom--The rapidly deployable boom, Figure 67, was designed by Headrick Industries of Glendale, California. It consisted of four 10-in.-diameter tubes each 250 ft long, arranged in the manner shown in Figure 68. The three top tubes were air-filled and the lower tube was water-filled, with bulkheads every 25 ft. A major feature of the Headrick boom was the cable harness, Figure 69, which kept the boom in a true V-shape while being towed.

(b) Heavy Duty Boom--The heavy duty boom, Figure 70, was designed and manufactured by Gates Rubber Company of Denver, Colorado. It consisted of a series of hose sections measuring 25 in. OD and 25 ft in length. The hose was bias-cut nylon tire cord carcass spirally wrapped onto a helix of 1/4-in.-diameter wire and bonded with neoprene rubber. A neoprene-coated nylon skirt was vulcanized to the bottom of the boom hose. The hose sections were terminated with aluminum heads, and sections could be connected by Marman (V-band) clamps, as shown in Figure 71.

(c) Water Spray Boom--The water spray boom, Figure 72, was designed and fabricated by Pacific Northwest Laboratories Division of Battelle Memorial Institute, Richland, Washington. It consisted of water spray nozzles mounted on five sponsons, as shown in Figure 73. The spray nozzles were mounted in a 6-in.-diameter pipe and sprayed water ahead of the sponsons at about a 20-deg angle from the horizontal.

SEA TESTS

Following is a description of the sea tests.

Test Location

The tests were conducted in three separate areas off the coast near Santa Barbara, as shown in Figure 74. Area A, which is immediately adjacent to the harbor, was used for general shake-down tests and closed-circuit skimmer oil tests. Since any oil spillage in this area would be noticed immediately, testing that would involve placing oil on the open ocean was not permitted.

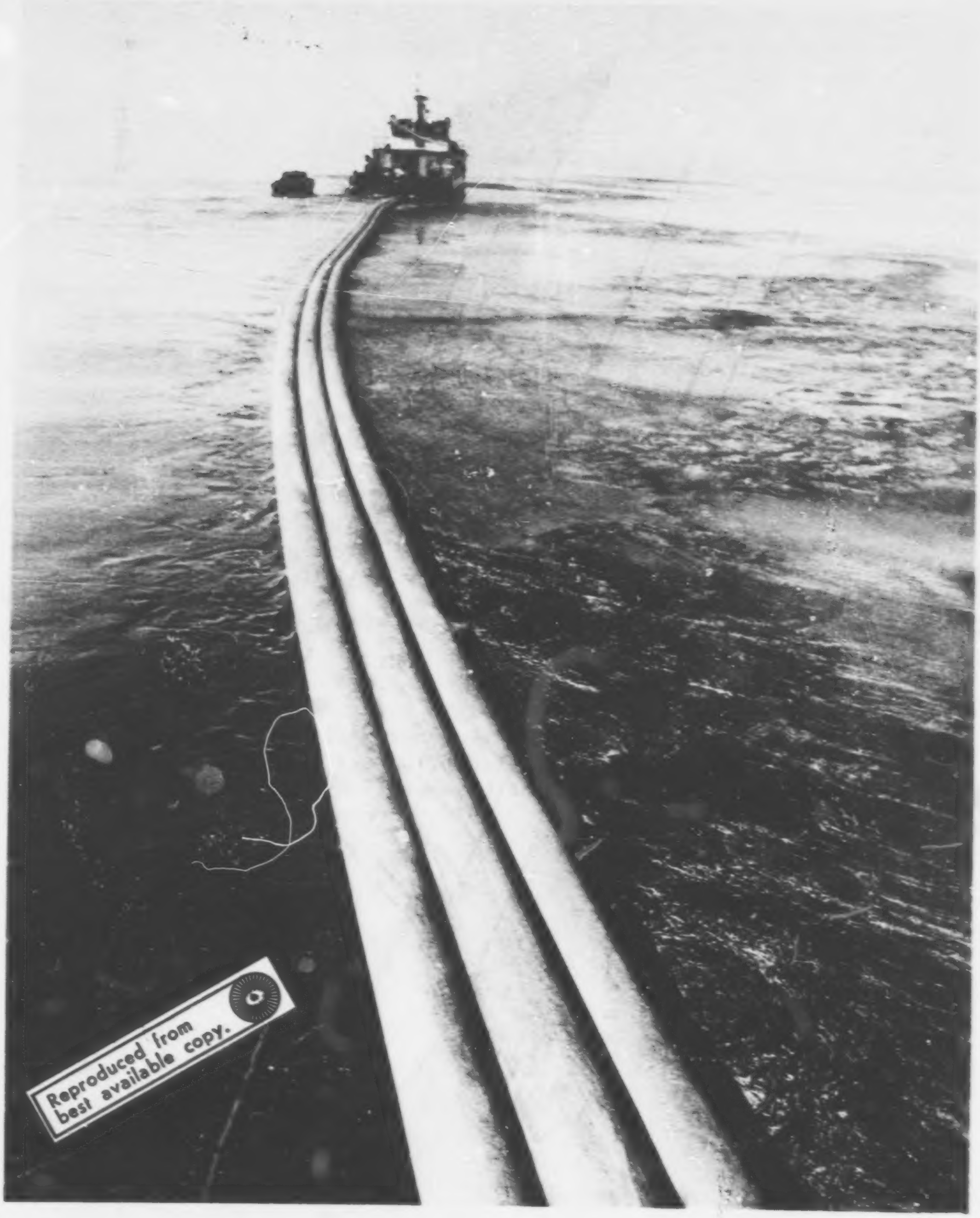

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Figure 67. Sweeping Oil with Single Headrick Boom

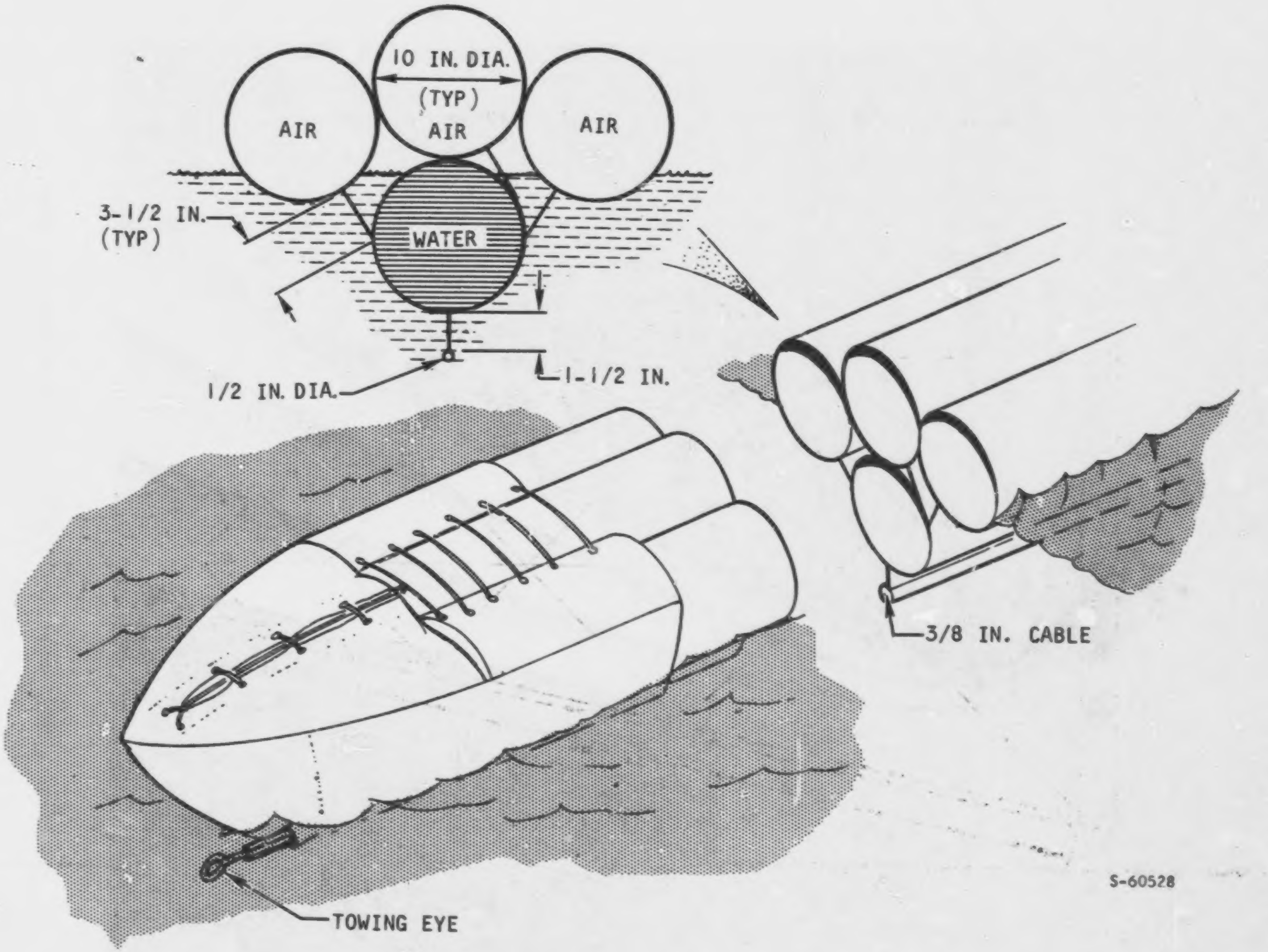

Figure 68. Headrick Inflatable Boom

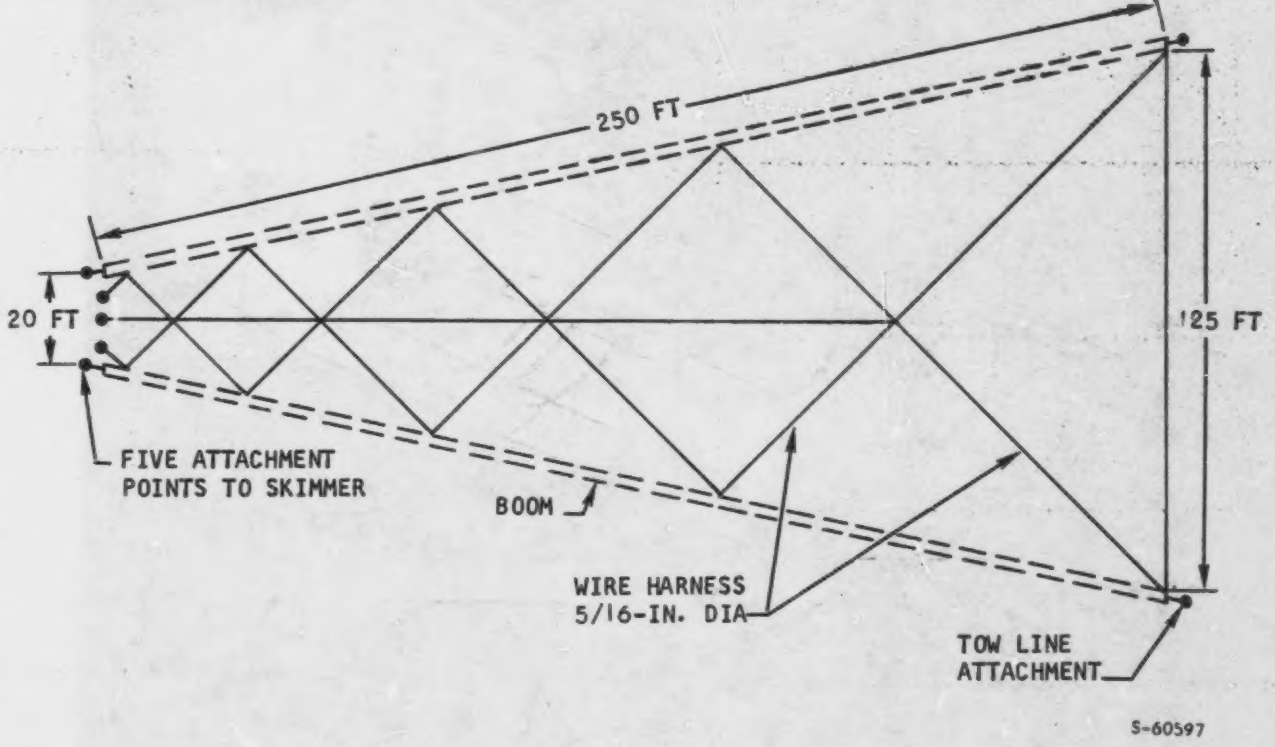

Figure 69. Headrick Boom Harness (Original Configuration)

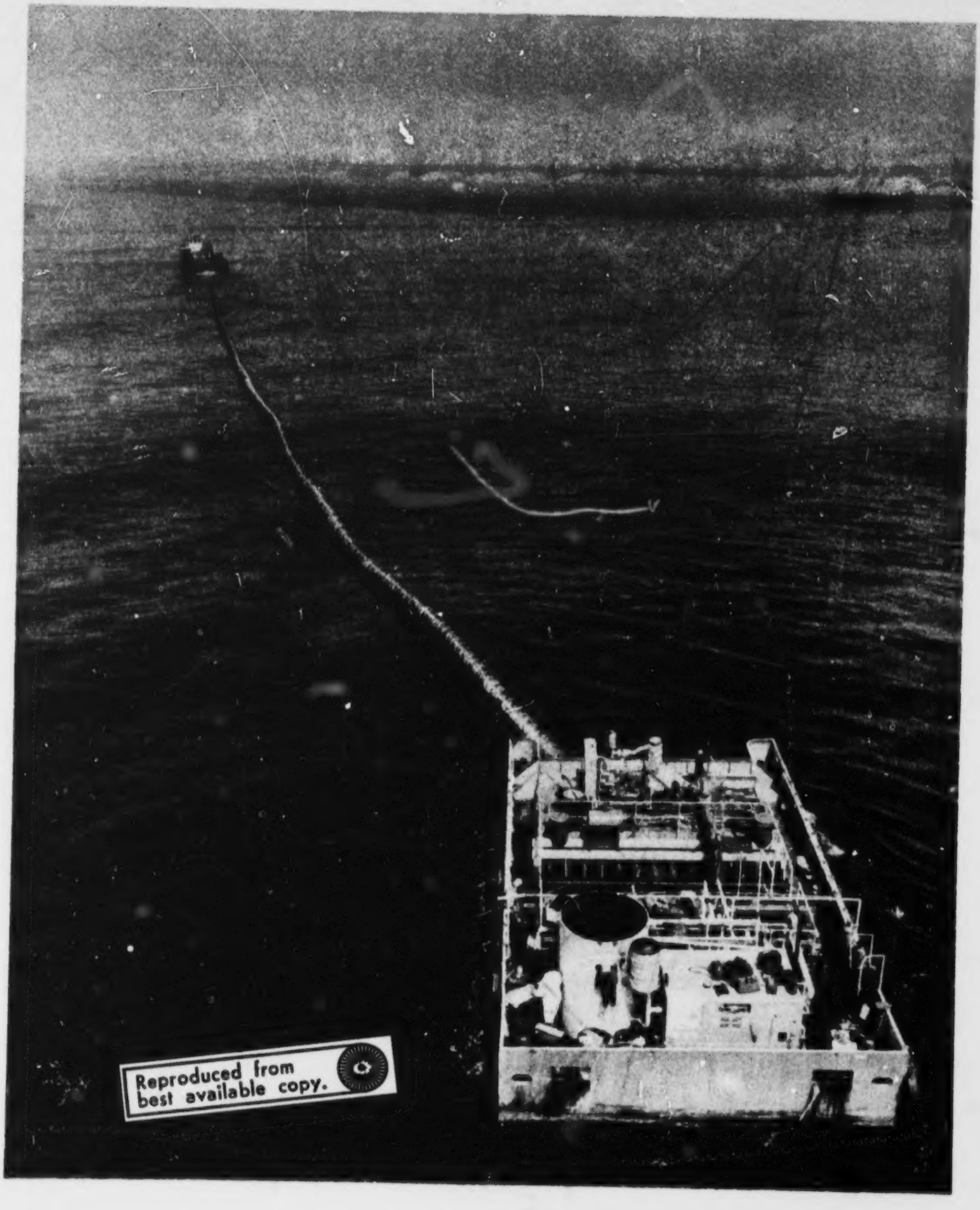

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Figure 70. Skimmer with Single 500-ft Section of Gates Boom

BOOM SIZE: LENGTH, 25 FT; DIAMETER, 25 IN.

BOOM WEIGHT: APPROX. 700 LB

BOOM MATERIAL: NEOPRENE COVERED NYLON (REINFORCED WITH WIRE AND FIBERGLAS)
ALUMINUM FLANGES AND END PLATES

INTERNAL PRESSURE: AMBIENT

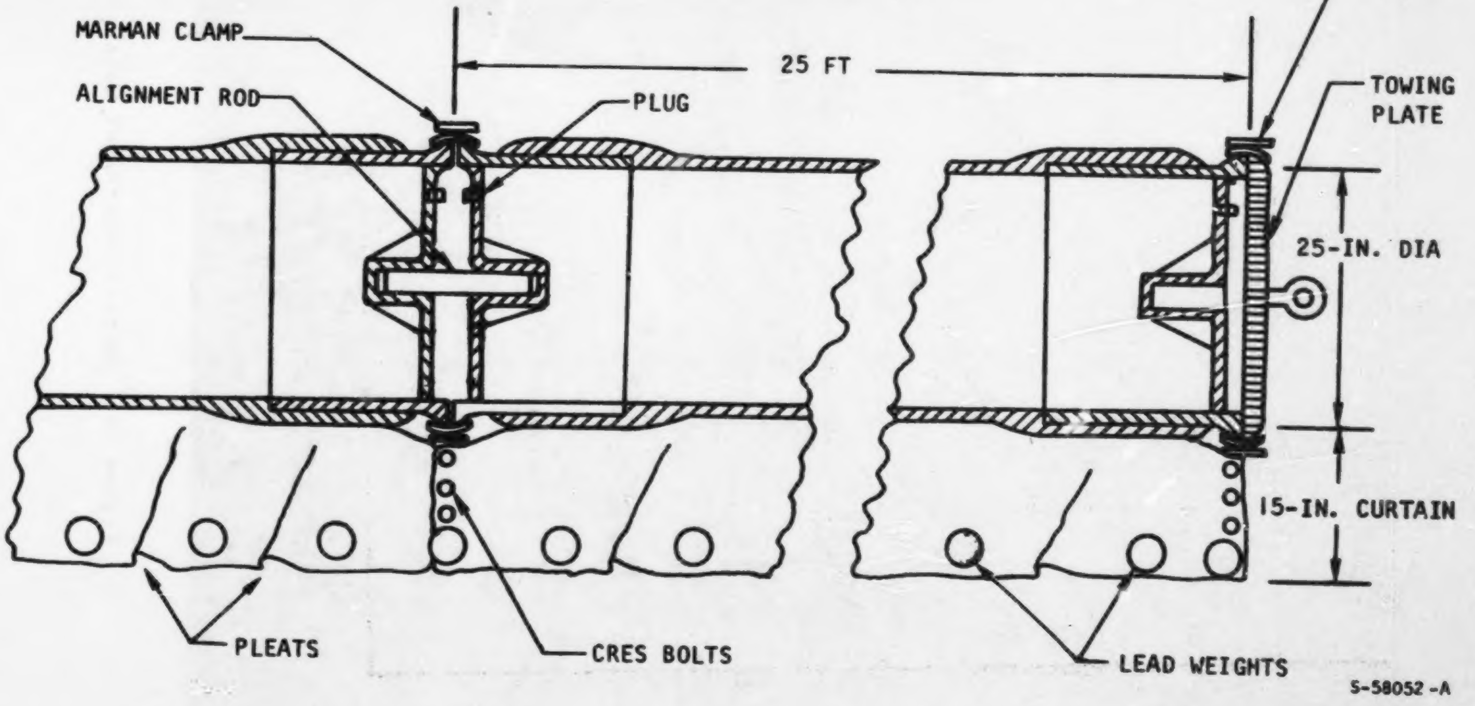

Figure 71. Gates Rubber Company Boom

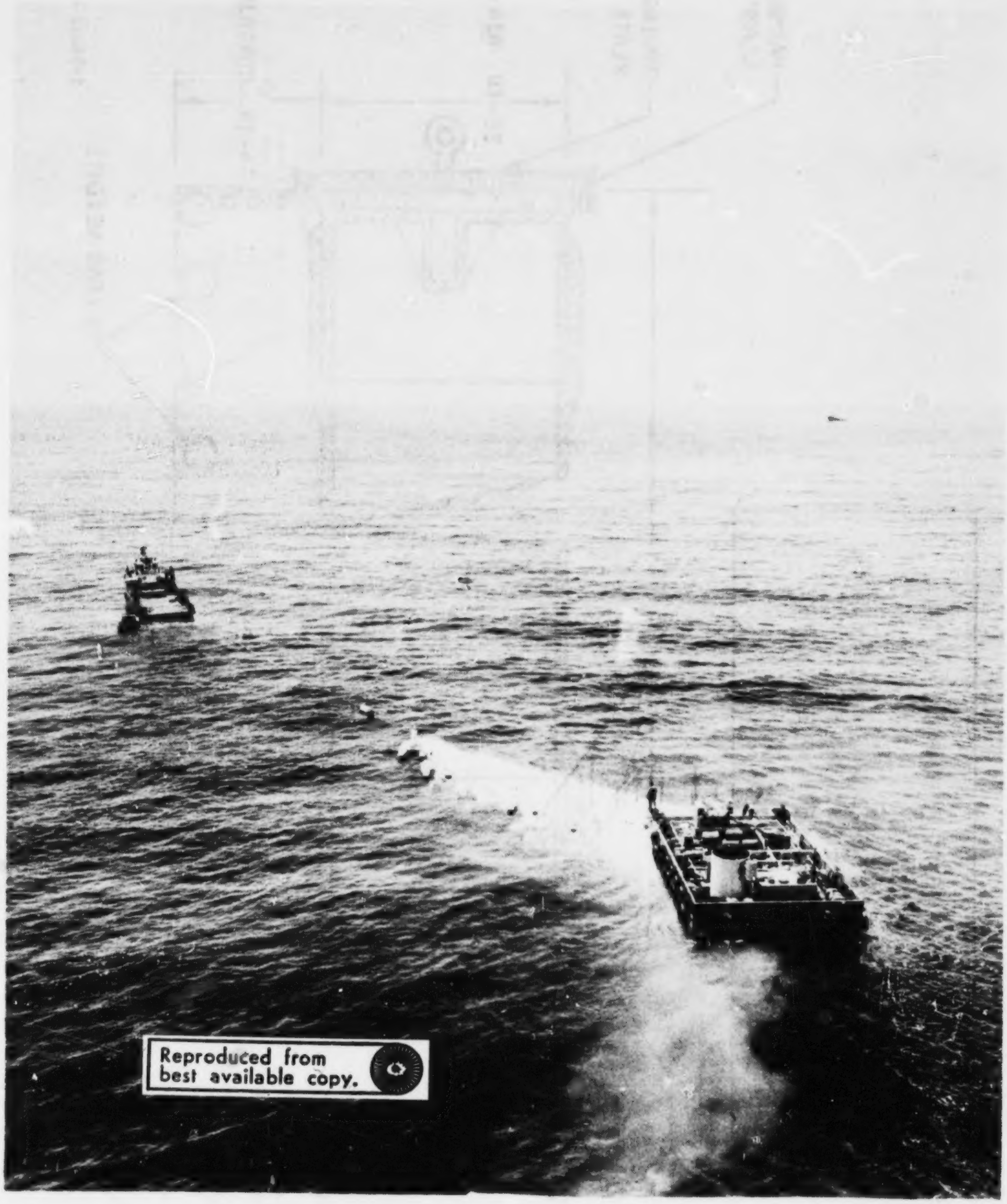

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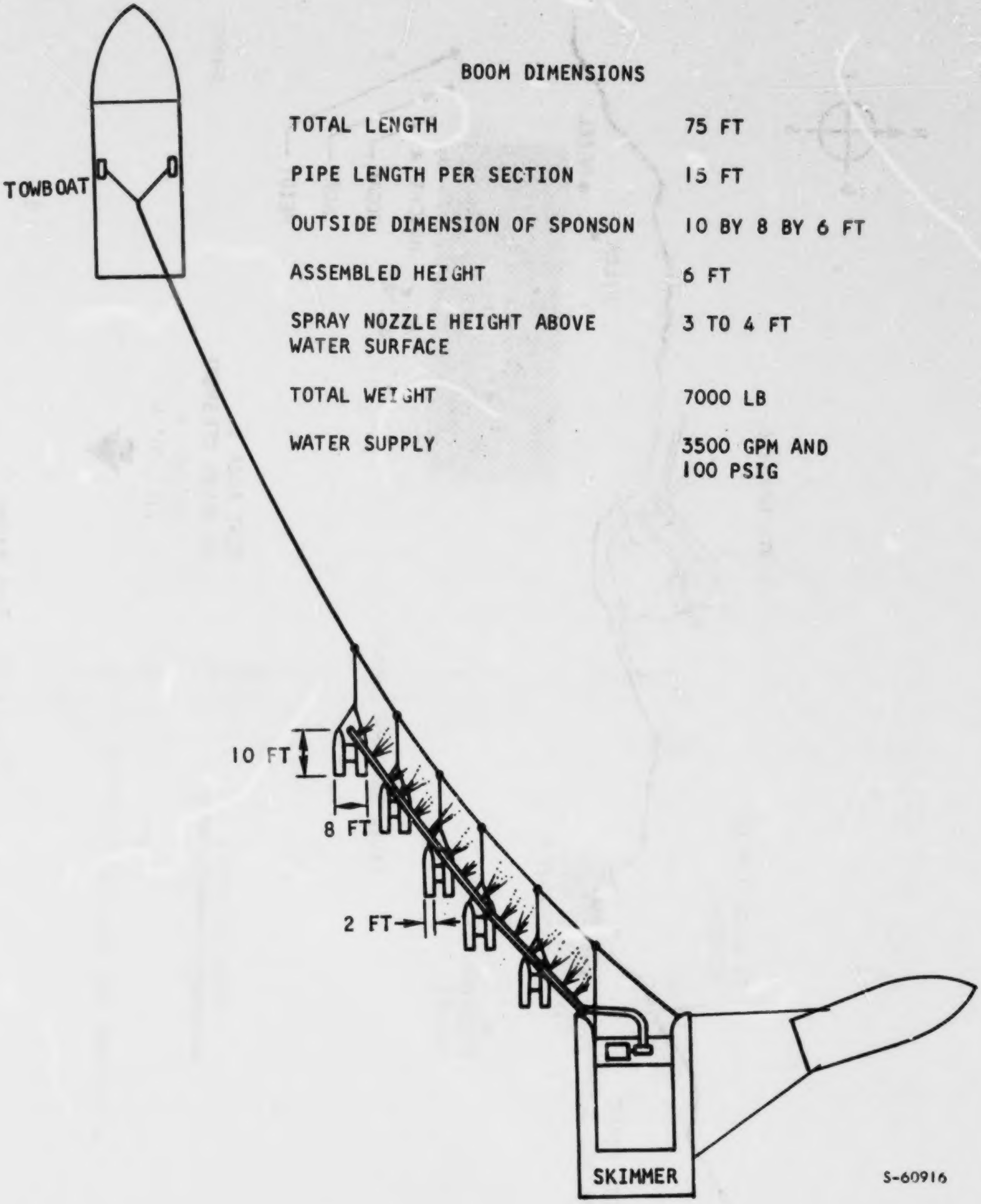
Figure 72. Battelle-Northwest Water Spray Boom



BOOM DIMENSIONS

TOTAL LENGTH	75 FT
PIPE LENGTH PER SECTION	15 FT
OUTSIDE DIMENSION OF SPONSON	10 BY 8 BY 6 FT
ASSEMBLED HEIGHT	6 FT
SPRAY NOZZLE HEIGHT ABOVE WATER SURFACE	3 TO 4 FT
TOTAL WEIGHT	7000 LB
WATER SUPPLY	3500 GPM AND 100 PSIG

Figure 73. Battelle Spray Boom during Skimming

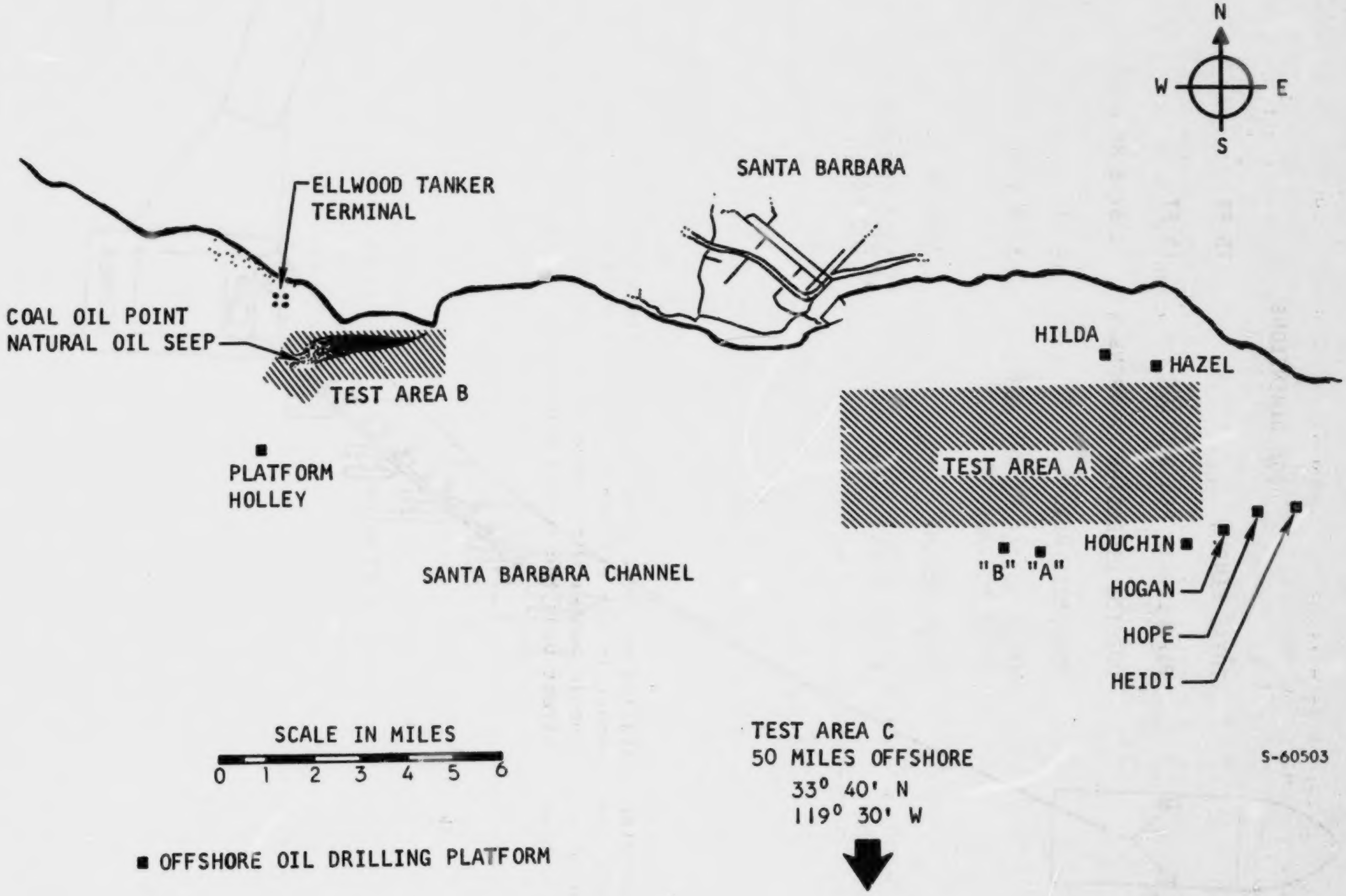


Figure 74. Test Areas

Area B is the site of a natural oil seep approximately 10 miles west of Santa Barbara. In this area a light weathered slick of several square miles is continuously present. The majority of the boom testing was done at this site, and some 26 and 35° API oil was occasionally dumped to test its effect.

The third location, Area C, was located more than 50 miles offshore. This area was used for the final system tests wherein oil was spilled on the ocean surface and then swept by the booms and recovered by the skimmer.

Testing was done with the technical assistance of representatives from the various subcontractors whose equipment was involved (Gates, Headrick, USCG). General Marine Transport supplied the boats, crews, and miscellaneous services required to support the operation.

Test Results

A summary of all of the testing at sea is presented in chronological order in Table 3. The skimming system, and usually the centrifuge, were in operation during many of the boom tests, so additional data under various operating conditions was obtained.

(a) Towing Tests

Sea testing of the skimmer commenced in June 1970. Early tests included towing tests at various speeds (forward and backwards) and at various depths (drafts). Figure 75 depicts the results of these tests against a background of the previously calculated predicted forces. The forces were measured with a dynamometer installed on the towing vessel in the manner shown in Figure 76. Of particular interest is the extremely small force involved in towing the skimmer at a reasonable boom-towing speed of one knot. This force is so low it would have no effect upon the tested booms, and the skimmer can be readily towed, at sweeping speed, through the booms. A separate towing line is not required for the skimmer.

(b) Skimmer Operation Tests

In order to check out the skimmer components a second series of tests, conducted in mid-June, included closed-circuit operation of the oil/water circuits. In these tests 15 or 26° API oil was introduced in the center of the spillway and circulated through the quiet pond, weirs, pumps, surge tank, and oil transfer pump back to the top of the spillway. It was observed that all components functioned.

(c) Centrifuge Tests

On June 16 the oil/water centrifuge was installed on the skimmer.

Since the centrifuge performance was mapped prior to installation on the skimmer, only sufficient data was taken to compare general adherence to previous data. For example, two test points taken during the at-sea test on June 18 using 26° API oil are shown on the performance map of Figure 66. A

TABLE 3

CHRONOLOGY OF TESTS

Date (1970)	Location*	Test	Test Objectives and Results
Jun 3	Area A	• Skimmer tow tests	• Skimmer towing forces. • Skimmer ballasting times. • Weir operation in Sea States 0 through 3.
Jun 9	Area A	• Skimmer closed-circuit oil tests • 26° API oil	• Quiet pond holds oil. • Floating weirs skim oil • Pumps pump weirs. • Surge tank separates oil and water to less than 25 ppm oil at gross flow rate of 50 gpm. • System pumps 500 gpm (but surge tank does not separate; centrifuge required).
Jun 11	Area A	• Skimmer closed-circuit oil tests • 16° API oil	• Lower API gravity oil much easier to process (will not mix with water as readily). • Sea States 0-2.
Jun 18	Area A	• Skimmer closed-circuit oil test with centrifuge using 26° API oil	• Centrifuge operated properly under barge pitch and roll environment. • Centrifuge separated oil from surge tank water discharge. • Sea States 0-3.
Jun 19	Area B	• Skimmer plus centrifuge and Gates boom with V harness	• Towing speed to test site was 5 to 6 knots. • Used natural oil seepage at Coal Oil Point. • Sea States 0-1.
Jun 24	Area B (Coal Oil Point)	• Skimmer and Gates boom with V harness	• Sea States 0-1.
Jul 23	Area B	• Single Gates boom and skimmer; no harness	• Two barrels of tar collected. • Weathered oil coagulates into large lumps of tar. Will not flow through weirs. • Sea State 0.
Jul 27	Area C (Off Santa Cruz Island)	• Skimmer efficiency tests	• Skimmer overall efficiency obtained with 35° API oil in Sea States 0 to 2.
Jul 29	Area C	• Skimmer and single and double Gates boom efficiency tests	
		• Skimmer and Headrick boom tests	• Headrick boom, with harness, swept oil at speed of 2.5 knots in Sea States 1 through 3.
Sept 23	Area B	• Single 250-ft section Headrick boom and skimmer with paddle wheel	• Made 75- to 100-ft wide sweeps at 2 knots. • Collected 18 barrels of tar from weathered natural seep. • Weirs and centrifuge ineffective with tar lumps. • Sea State 0.
Sept 24	Area A	• Single 250-ft section Headrick boom and skimmer with paddle wheel	• Made 75- to 100-ft wide sweeps at 2 knots. • Collected 5 barrels of weathered oil (tar) from accumulated leakages in this area. • Weirs and centrifuge ineffective in tar lumps formed from weathered oil. • Sea State 0.

*See Figure 74.

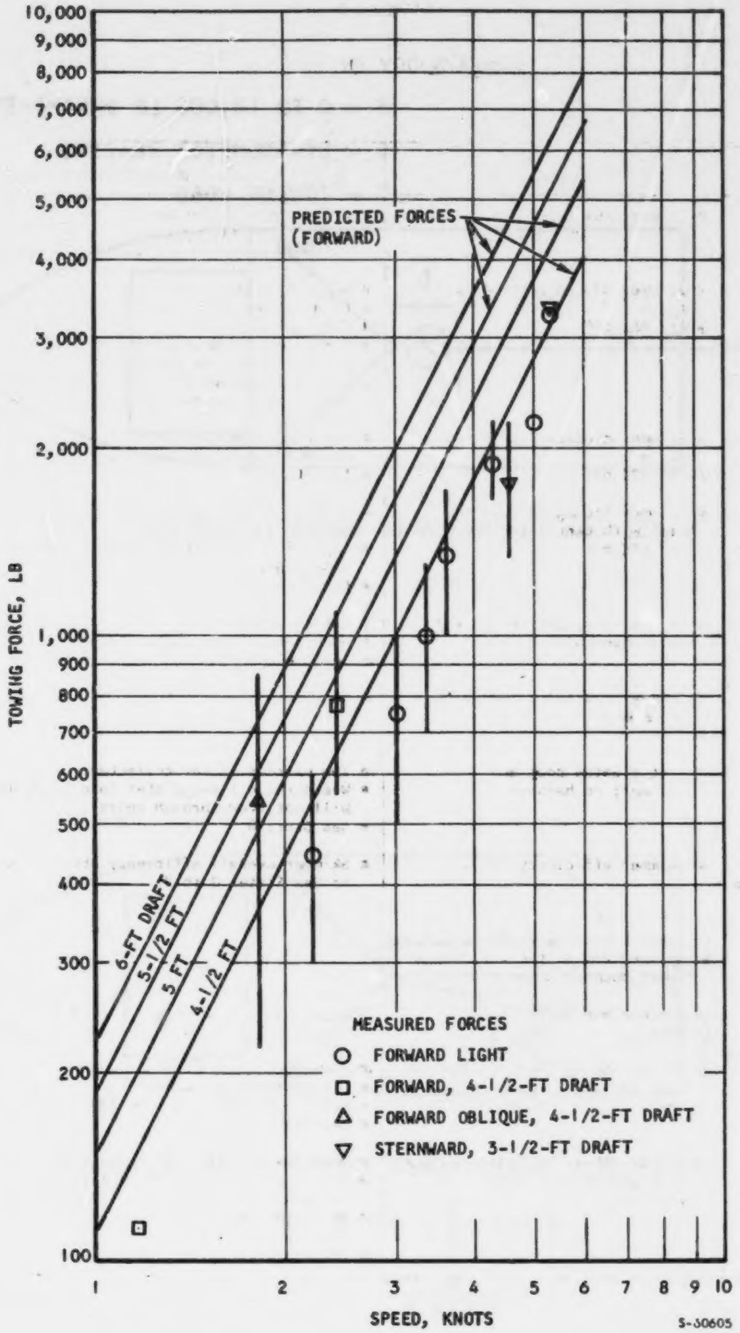
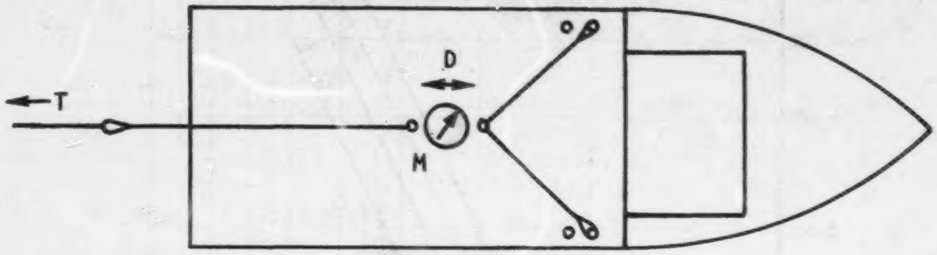


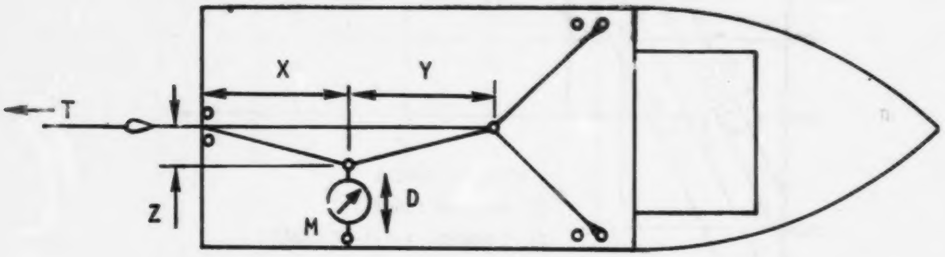
Figure 75. Barge Towing Forces

M = 0 TO 10,000 LB DYNAMOMETER
D = DYNAMOMETER READING
T = TOWING LOAD



SET FOR TOWING LOADS UNDER 10,000 LB

$$T = D$$



SETUP FOR TOWING LOADS GREATER THAN 10,000 LB

$$X = Y; \frac{Z}{X} = \tan\theta$$

$$T = \frac{D}{2 \sin\theta}$$

S-60502

Figure 76. Dynamometer Setup for Measuring Towing Forces

typical result of these tests is shown in Figure 77. The jar on the right contains the centrifuge inlet mixture (approximately 2 percent oil), the center jar contains the oil discharge, and the left-hand jar water discharged by the centrifuge. During this time period, skimmer barge equipment was further developed to improve the handling of the oil/water/trash mixtures.

After these tests were completed the skimmer was assigned to the API boom testing program.

(d) Skimmer Tests with Boom

The skimmer was tested with the Gates, Headrick, and Battelle booms already described. Use of the Gates and Headricks booms enabled a wide expanse (greater than 100 ft) of ocean surface to be swept into the skimmer. It was observed that oil spread on the ocean surface would weather in just a few hours to a tar-like product. Although the oil on the ocean surface appeared to be very light and thin (with a silvery sheen, color bands, and some "elephant skin" windrows), it was actually made up of the weathered heavy ends. As it collected in the quiet pond it coagulated into a heavy black sponge-like mass several inches thick. Some of this was skimmed off by the floating weirs and pumped to the surge tank. However, the weirs quickly became clogged with the thick masses of tar and the material had to be manually broken up and lifted from the quiet pond like pieces of asphalt paving.

Oil that was pumped to the surge tank rapidly coagulated on the surface and would not drain off through the 3-in.-diameter oil drain pipe. This material had to be shoveled into open oil drums. A quart jar sample of the oil could be inverted without the oil running out. A total of 18 barrels of this material was collected during a 4-hr period on September 23, 1970. Two samples taken during this test period had these characteristics:

	Sample No. 4	Sample No. 9*
Sample location	Quiet pond	Collecting drum
Date	Sept. 23, 1970	Sept. 25, 1970
Time	10:00 a.m.	2:00 p.m.
Percent water	38 percent (including 11 percent sand)	26 percent (including 4 percent sand)
Specific gravity	1.0557	1.0507
API gravity	2.5°**	4.5°**
Appearance	Wet mass of tar	Damp mass of tar

---

*Material collected at Coal Oil Point Sept. 23, 1970 and placed in drums.

**Oil of these gravities is denser than sea water and should sink. Samples taken at Coal Oil Point and stored in 1-pt Mason jars usually sink within a day or two. Apparently entrapped gas keeps this material afloat.

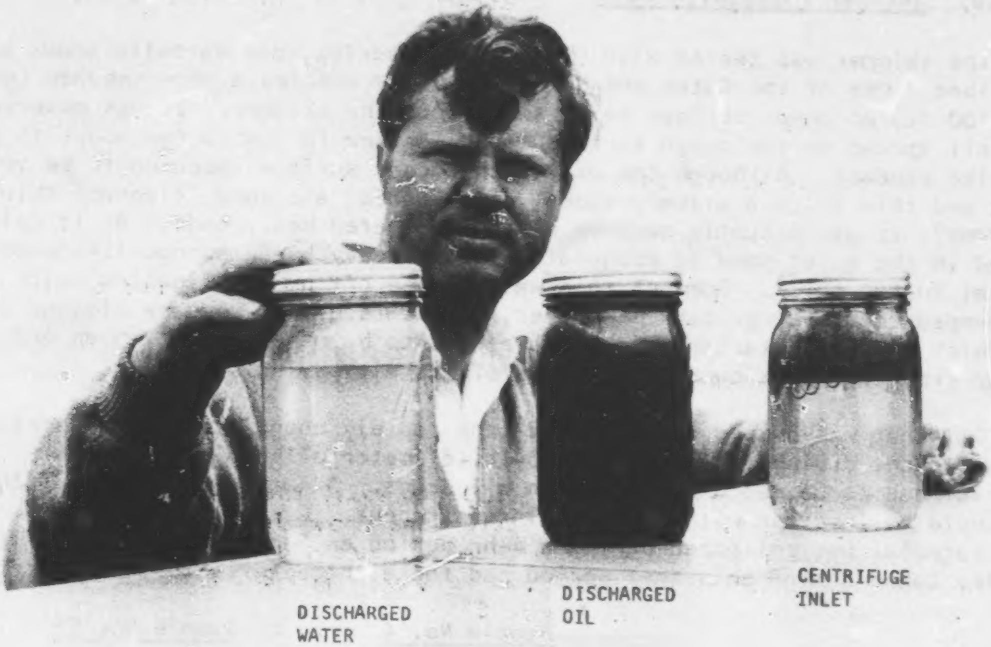


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Figure 77. Centrifuge Inlet and Discharge Samples

(e) Skimmer Efficiency Tests

During the sea tests conducted July 27 to 30, 1970, the overall collection efficiency of the skimmer was determined for a particular set of conditions. The skimmer was deployed off the stern of the supply boat Sea Tender in the manner shown in Figure 78, and oil was dumped in front of the skimmer by means of a 3/4-in. hose attached to the towline. The oil circuit is shown in Figure 79.

Overall skimmer efficiency is dependent upon all of these factors:

(a) Skimmer speed

(b) Sea state

(c) Direction with respect to wind and waves

(d) Depth of spillway

(e) Condition of inlet as affected by booms, etc., in front of the skimmer

(f) Oil film thickness

(g) Oil gravity

During the test period between 13:30 and 15:30 the skimmer was progressing at 1.2 knots starting under Sea State 0 as shown in Figure 80. As the test proceeded, the sea state condition gradually increased until at the termination of the test at 16:30, the sea state was between 1 and 2. Results of the efficiency testing are shown in Figure 81.

The rate of dump was determined by recording the total quantity (barrels) passed through a flowmeter on the dump hose and applying a meter correction as determined by a calibration of the flowmeter at the Signal Oil Company Laboratory in Long Beach, California.

Meter calibration:

10 bbl actual = 10.45 bbl indicated

Meter correction:

$$\frac{\text{Meter Reading}}{10.45} = \text{actual bbl}$$

These points are plotted in Figure 81.

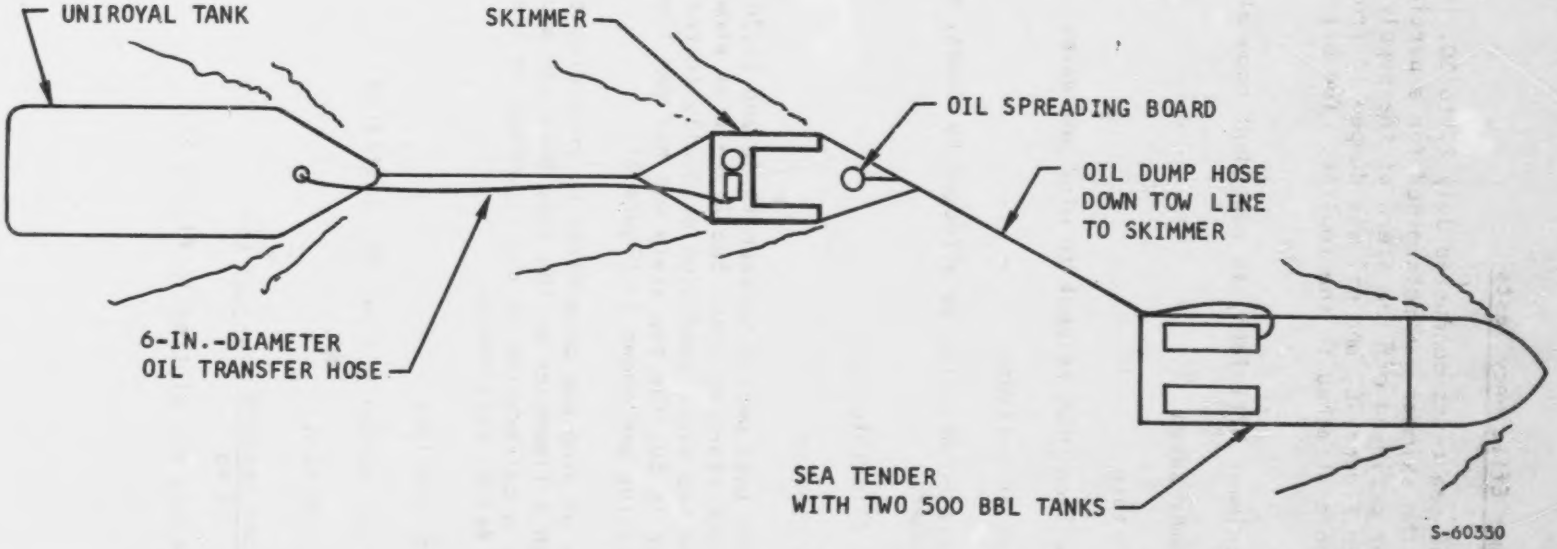
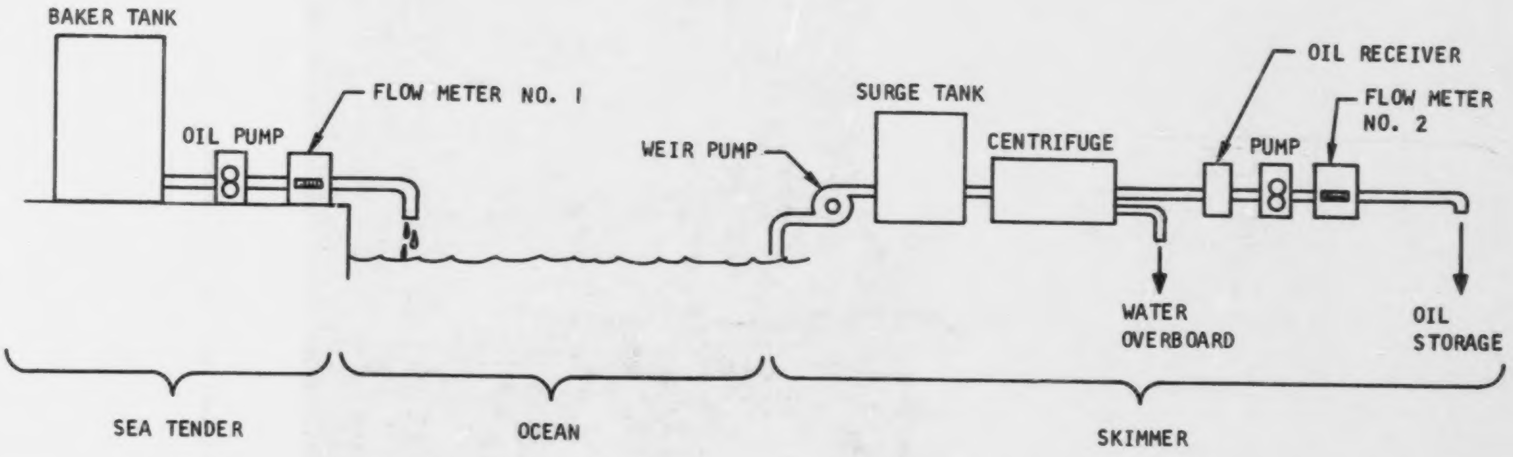

UNIROYAL TANK
SKIMMER
OIL SPREADING BOARD
OIL DUMP HOSE DOWN TOW LINE TO SKIMMER
6-IN.-DIAMETER OIL TRANSFER HOSE
SEA TENDER WITH TWO 500 BBL TANKS
S-60330

Figure 78. Skimmer Efficiency Test Setup



$$\frac{\text{FLOW METER NO. 2}}{\text{FLOW METER NO. 1}} \times 100 \times K = \text{EFFICIENCY}$$

K = CORRECTION FACTOR FOR WATER CONTENT AND LIGHT END LOSS.

S-60335

Figure 79. Setup for Determination of System Efficiency

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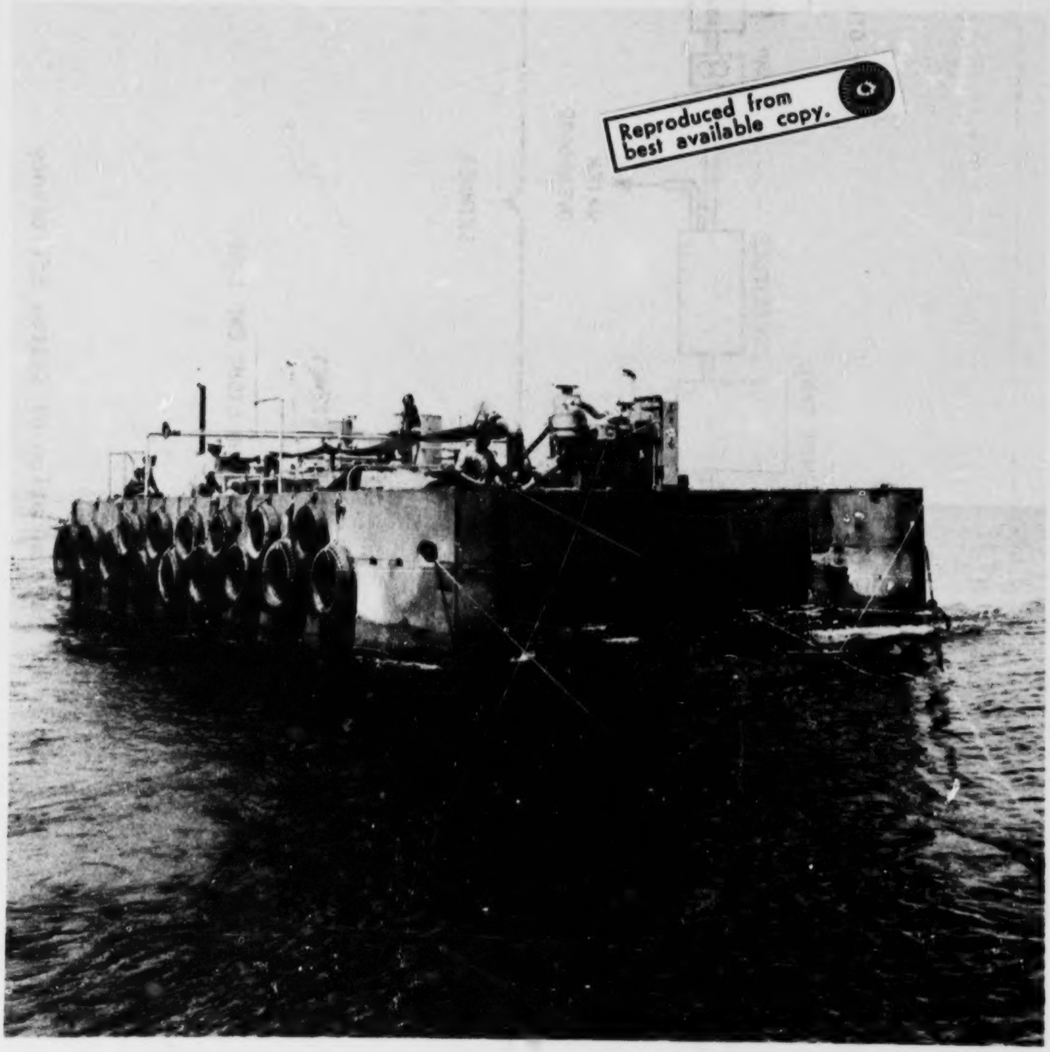


Figure 80. Skimmer during Efficiency Test

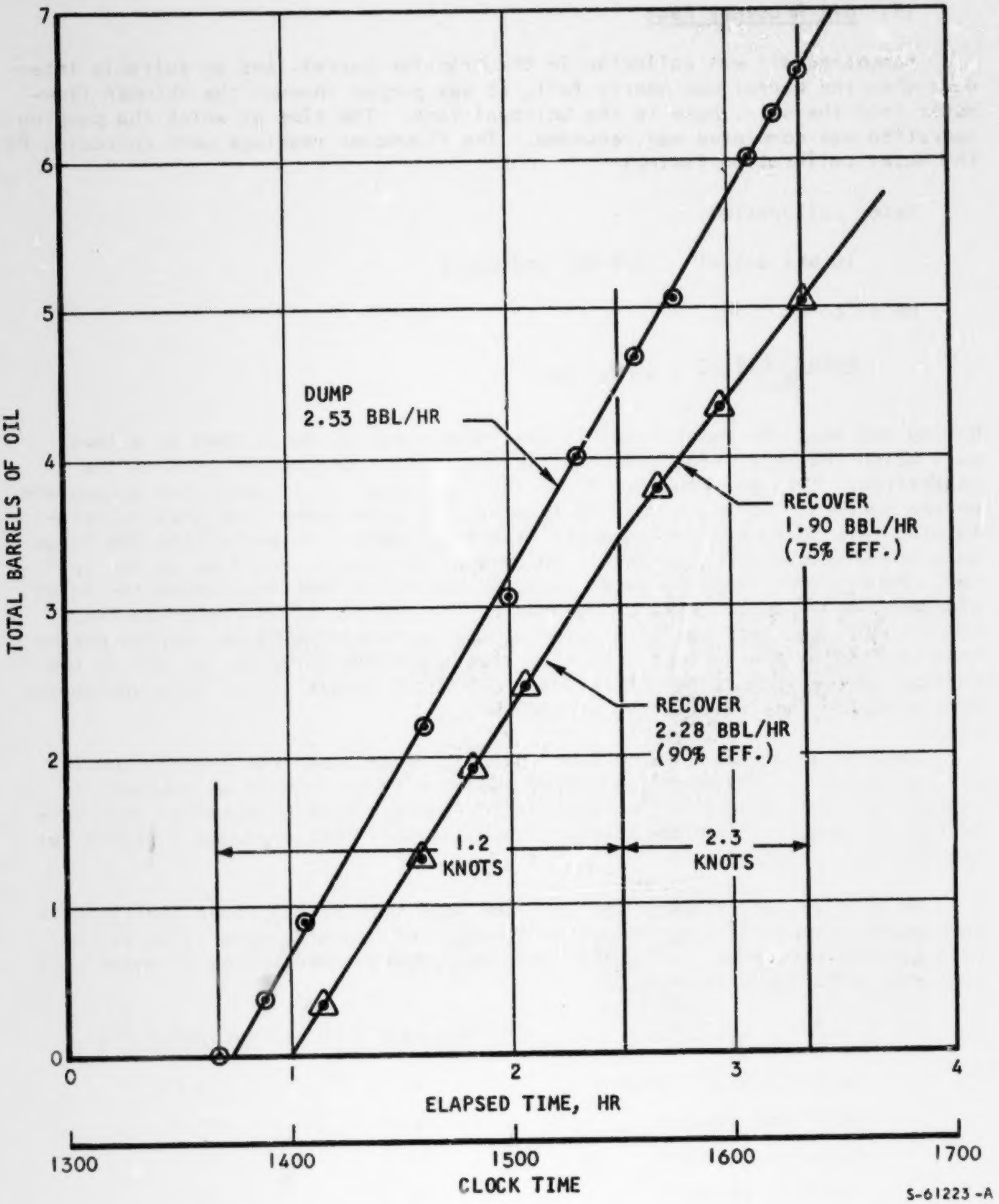


Figure 81. Skimmer Efficiency Test

(f) Oil Recovery Rate

Recovered oil was collected in the transfer barrel, and at suitable intervals when the barrel was nearly full, it was pumped through the skimmer flowmeter into the 6-in. hose to the Uniroyal tank. The time at which the pumping operation was completed was recorded. The flowmeter readings were corrected by the meter calibration factor:

Meter calibration:

10 bbl actual = 10.8 bbl indicated

Meter correction:

$$\frac{\text{Meter reading}}{10.8} = \text{actual bbl}$$

During the test the water level in the surge tank was maintained at a level well below the inlet pipe and a little above the lower outlet pipe to the centrifuge. This kept the oil mixed into the water so it would not accumulate on the surface. At approximately 1600 hr, the crew member assigned to maintaining this level had to leave his station to assist in ballasting the barge to a somewhat deeper waterline in an attempt to reduce underflow at the spillway. During this time the water level in the surge tank rose above the inlet pipe and, as a result, oil accumulated on the surface of the water in the surge tank. The test was terminated at 1620 hr when the barge towline parted from chafing at the towboat. At this time there was 1-1/2 in. of oil on the surface of the surge tank. This quantity, which is 5/8 (0.63) bbl, was therefore added to the last reading at 1620 hr.

Samples of oil were taken from the centrifuge discharge intermittently during the test. These were analyzed and were found to have an average oil content of 78.5 percent. The recovered oil/water emulsion data was then corrected for water content by multiplying by 0.785. This produced a figure for the dry oil collected.

On July 29, while operating with the same type of oil under similar circumstances except that a boom was being used, oil samples were taken of the original and recovered oil. These were analyzed for percentage of major constituents with these results:

	Original Oil	Recovered Oil
Sulfur, weight percent	0.15	0.25
Gasoline, percent	33.9	15.9
Kerosine, percent	22.7	26.5
Gas-oil, percent	22.0	28.8
Still residue, percent	21.7	27.6
Loss, percent	1.3	1.2

(See Tables 4 and 5 for complete data)

TABLE 4

GENERAL CRUDE OIL TESTS ON OIL SAMPLES SUBMITTED BY AIRESEARCH MANUFACTURING COMPANY

	Original Oil 1842	Recovered Oil 1842 7/29/70 V
API gravity, 60 F	33.5*	28.5
Specific gravity, 60/60 F	0.8576	0.8844
Pour point, F	+35	+55
Sulfur, weight percent	0.15	0.25
Viscosity, SUS		
70 F	55.0	105.9
100 F	44.1	60.3
Initial boiling point	126	213

---

*The corrected API gravity of the tank sample of the oil delivered on July 24, 1970 was 34.9° API and has been regarded as 35° API throughout this report. This particular sample, taken after five days at sea in a vented 250-barrel tank, indicated 33.5° API.

Assuming that no evaporation or solution of the gas-oil constituent occurred, the loss of the other constituents and the quantity of original oil per unit volume of the recovered sample can be determined. With this assumption, 23.7 percent of the original oil spilled was lost through evaporation or solution. Assuming that 5 percent of the gas-oil constituent was also lost, the total loss would increase to 27.5 percent. This analysis is shown below:

(1) No Gas-Oil Loss

The original oil sample was 22.0 percent gas-oil and the recovered sample was 28.8 percent gas-oil. If it were assumed that no gas-oil was lost, the original volume of crude represented by the recovered sample would have been 131 ml/100 ml recovered:

$$\frac{28.8}{22.0} = 1.31$$

TABLE 5

MODIFIED HEMPEL DISTILLATION OF OILS SUBMITTED BY AIRESEARCH MANUFACTURING COMPANY

Atmospheric Distillation Temp., F	Original			Recovered		
	Percent Distilled	Total Percent Distilled	API Gravity	Percent Distilled	Total Percent Distilled	API Gravity
IBP-122	-	-	-	-	-	-
122-167	1.0	1.0	76.4	-	-	-
167-212	3.4	4.4	62.2	-	-	-
212-257	7.8	12.2	55.8	1.8	1.8	44.6
257-302	7.9	20.1	51.9	3.0	4.8	46.7
302-347	7.6	27.7	48.5	4.8	9.6	45.7
347-392	6.2	33.9	45.1	6.3	15.9	45.3
392-437	6.1	40.0	41.8	8.8	24.7	41.6
437-482	8.1	48.1	34.8	10.1	34.8	37.8
482-527	8.5	56.6	35.6	7.6	42.4	35.3
Vacuum Distillation, 40 mm Hg., F						
Up to 392	2.5	59.1	32.7	3.1	45.5	32.8
392-437	5.1	64.2	31.5	7.4	52.9	31.6
437-482	5.3	69.5	29.3	6.5	59.4	29.1
482-527	4.3	73.8	26.9	5.6	65.0	27.1
527-572	4.8	78.6	23.5	6.2	71.2	24.8
Distillation Summary						
Gasoline	-	33.9	52.3	-	15.9	45.7
Kerosine	-	22.7	38.2	-	26.5	38.7
Gas Oil	-	22.0	28.6	-	28.8	28.8
Still Residue	-	21.7	11.7	-	27.6	9.4
Error or Loss	-	-0.3	-	-	1.2	-

A 131-ml sample of original crude would contain the quantities of constituents as shown in line 2 of Table 6. Actually the amounts recovered were as shown in line 3. Line 4 shows the percentage of each of the original constituents recovered, and line 5 the percentage loss.

(2) Five Percent Gas-Oil Loss

If it were assumed that some of the gas-oil was also lost, these loss figures would be even higher. As an example, lines 6 through 8 of Table 6 illustrate the case in which a loss of 5 percent of the gas-oil is assumed and the original gas-oil amount would be 30.3 ml for each 28.8 ml recovered.

Since the oil placed on the water for the efficiency tests would be subject to the same loss phenomena, although for varying exposure times, it was assumed that an average evaporation and solution loss of 20 percent had occurred. Therefore, the dry oil figures were corrected by dividing these values by 0.80 to obtain a value for the equivalent original oil collected. This is plotted as the "recover" curve of Figure 81. A summary of the test data and the calculations from which these curves were plotted is included as Table 7.

From observations of these tests in comparison to those at Coal Oil Point it appeared that the 35° API oil mixes very easily with water forming small droplets that were readily carried below the surface. The heavier Coal Oil Point oil, or weathered oil, tended to form larger globules, which tended to stay on the surface of the water and not be carried under the skimmer.

(g) Paddle Wheel Tests

On September 16, 1970 a paddle wheel was installed as shown in Figures 35 and 36. It was driven by a V-belt gear-reducer chain-drive assembly by means of a small diesel engine removed from one of the weir pumps. The overall drive ratio was 119:1 in three steps as follows.

V-belt 5/8 = 0.625:1

Worm gear reducer = 30:1

Chain 70/11 = 6.36:1

Overall = 0.625 x 30 x 6.36 = 119:1

The diesel engine could be run at speeds between 900 and 3600 rpm, but all of the testing was done at a constant engine speed of 1460 rpm. This produced a peripheral speed on the 36-in.-diameter paddle wheel of 1.2 knots. This speed appeared to be most compatible with the 2.0-knot skimmer velocity used during the tests.

TABLE 6

SUMMARY OF EVAPORATION LOSS CALCULATION

Line		Gasoline	Kerosine	Gas-Oil	Residual	Error	Total
100 percent of gas-oil recovered							
1	New oil sample percent	33.9	22.7	22.0	21.7	-0.3	100.0
2	ml	44.5	29.8	28.8	28.4	-0.4	131
3	Recovered oil sample percent	15.9	26.5	28.8	27.6	1.2	100.0
4	Percent recovered	35.7	89.0	100.0	97.3	-	76.3
5	Percent lost	64.3	11.0	0.0	2.7	-	23.7
95 percent of gas-oil recovered							
6	Size of original sample per 100 ml recovered	46.6	31.2	30.3	29.8	-0.4	137.5
7	Percent recovered	34.1	85.0	95.0	92.7	-	72.7
8	Percent Lost	65.9	15.0	5.0	7.3	-	27.3

TABLE 7

SUMMARY OF RESULTS OF SKIMMER EFFICIENCY TEST JULY 27, 1970

Test Time (Hr)	Sea Tender Flowmeter (bbls)	Oil Dumped (Uncorrected) (bbls)	Oil Dumped (Meter Corrected) (bbls)	Oil Transfer Pump	Skimmer Flowmeter (bbls)	Flowmeter bbls Collected	Flowmeter Collected (bbls)	Plus 5/8 bbl in Surge Tank At end of Test	Corrected For Water Content	Corrected for Evaporation
1340	22.3	-	-							
1345	22.4	0.1	0.10							
1353	22.7	0.4	0.38							
1404	23.2	0.9	0.86							
1406				Start	3.50	-0-		-	-0-	-0-
1407										
1409				Stop	3.90	0.40	0.37	-	0.29	0.36
1417				Start	3.90					
1436				Stop	4.95	1.45	1.34	-	1.05	1.31
1437	24.6	2.3	2.20							
1448				Start						
1450				Stop	5.64	2.14	1.98	-	1.55	1.94
1451					5.64					
1500	25.5	3.2	3.06							
1502				Start						
1504				Stop	6.22	2.72	2.52	-	1.98	2.47
1519	26.5	4.2	4.02							
1535	27.2	4.9	4.68							
1539				Start						
1541				Stop	7.68	4.18	3.87	-	3.04	3.80
1542					7.68					
1545	27.6	5.3	5.06							
1556				Start						
1558				Stop	8.26	4.76	4.41	-	3.46	4.33
1559					8.26					
1606	28.6	6.3	6.02							
1613	28.9	6.6	6.30	Start						
1616				Stop		4.93	4.56			
1620	29.2	6.9	6.58					5.19	4.07	5.08
1630					8.43					

It was observed that the paddle wheel was able to maintain a flow into the skimmer inlet even when the skimmer was standing still in the water. After the checkout runs were made alongside the pier in Santa Barbara, it was noted that another boat in the harbor had discharged several gallons of black oil while pumping tanks. The skimmer, which lay immediately downwind of the offending vessel, was submerged to operational depth and the paddle wheel started. Garden hoses and spray nozzles fed by the skimmer's high pressure (60 psig) water supply were employed to direct the spill to the front of the skimmer. The paddle wheel maintained a flow into the quiet pond and the entire spill was collected without moving the skimmer from its mooring.

During the at-sea tests on September 23, and 24, the paddle wheel maintained a constant flow across the spillway lip appreciably increasing the flow of oil into the skimmer. Furthermore, the paddle wheel did not cause the severe wave reflections as did the wave gate previously used. As the skimmer became increasingly loaded with the collected weathered oil, the paddle wheel became an effective check valve to prevent the oil from passing back out through the entrance when the skimmer stopped.

SECTION IX

DISCUSSION

The skimmer barge and centrifuge recovered and separated oil in Sea States 0 through 3. The effectiveness of the skimming system was reduced as the sea state increased and although no efficiency data was taken, the system was shown operable in Sea State 3. In rougher seas the floating weirs had to be secured to prevent damage from sloshing, but under these conditions, they become quite inefficient anyway. If the floating weirs were replaced by a fixed weir, the skimming could continue, although at reduced efficiency, until the barge began to take water over the gunwales in large amounts (estimated Sea State 7).

The quality of the oil being recovered had a marked effect on the operation. Light oils of 26 to 35^0 API were readily passed through the system. However, they appeared to readily emulsify. Heavier oils separated readily in the surge tank so that the centrifuge inlet emulsion appeared to contain a low percentage of oil. The weathered oils, which had the consistency of tar, were very difficult to handle within the skimmer, but were so cohesive the collection efficiency appeared to be perfect. This material required manual recovery, as it formed into lumps too large to pass through the weirs. Additional equipment would have to be installed on the barge to handle this material.

SKIMMER BARGE

Effect of Wave Action

The skimmer barge was operated in seas from flat calm to Sea State 3 (with 4-ft waves), and the waves had these effects on the skimming effectiveness:

(a) Increasing wave heights would increase the surface disturbance at the entrance to the skimmer, thereby causing the oil to be mixed into the surface water prior to entrance into the skimmer. This phenomenon was aggravated by the higher gravity, noncohesive oils.

(b) Waves entering the skimmer were observed to cause disturbances in the quiet pond, which would tend to prevent complete settling. This was particularly noticeable at the forward end of the quiet pond, especially when the wave gate was being used. These disturbances were observed to extend all the way to the bottom of the quiet pond and would cause some oil to escape through the louvered bottom.

(c) Visually, the pitching, rolling, and heaving of the barge due to wave action had minor effects. These motions caused sloshing in the quiet pond, which was partially attentuated by the wave fences.

(d) The paddle wheel was not tested in sea states high enough to determine its relative effectiveness in reducing wave disturbances at the skimmer entrance. Results of testing with the paddle wheel in lower sea states, however, indicate that it might reduce the vertical currents generated immediately aft of the spillway more effectively than does the wave gate. The paddle wheel, on the other hand, would not offer the full protection available with a completely closed wave gate under very high sea states.

Loss of Oil

The principal phenomenon that affected skimmer efficiency was loss of oil at the front of the quiet pond. This was due to the extreme turbulence and vertical circulation immediately aft of the spillway and in the region of the first wave fence, as shown in Figure 82. Oil droplets would beat into the water while passing the disturbed areas of the wave gate, the aft side of the spillway, and the wave fences. Vertical circulation, caused by the aft side of the spillway, carried these oil droplets to the bottom of the quiet pond where they escaped through the forward louvers. This phenomenon was observed through the underwater viewing ports in the sides of the quiet pond.

Oil was observed to be lost through the bottom of the quiet pond in quantities sufficient to leave an easily discernible slick behind the barge when processing oil in the 26 to 35° API gravity numbers. Observation through the underwater viewing ports showed that this is a phenomenon restricted to the forward end of the pond.

It is anticipated that this shortcoming can be eliminated by some minor modification to the forward end of the quiet pond. Changes that could be considered, as shown in Figure 83, are:

(a) Closing the louvers for the first several feet of the quiet pond

(b) Installing horizontal baffles in the forward section of the quiet pond to reduce vertical circulation

(c) Improving adjustment of the wave gate to reduce water disturbance

(d) Extending the spillway slope to better diffuse the incoming stream and to reduce the effect of the vertical aft bulkhead of the spillway

Seaworthiness of Barge

No problems were encountered with respect to the stability or seaworthiness of the skimmer barge during the tests at sea.

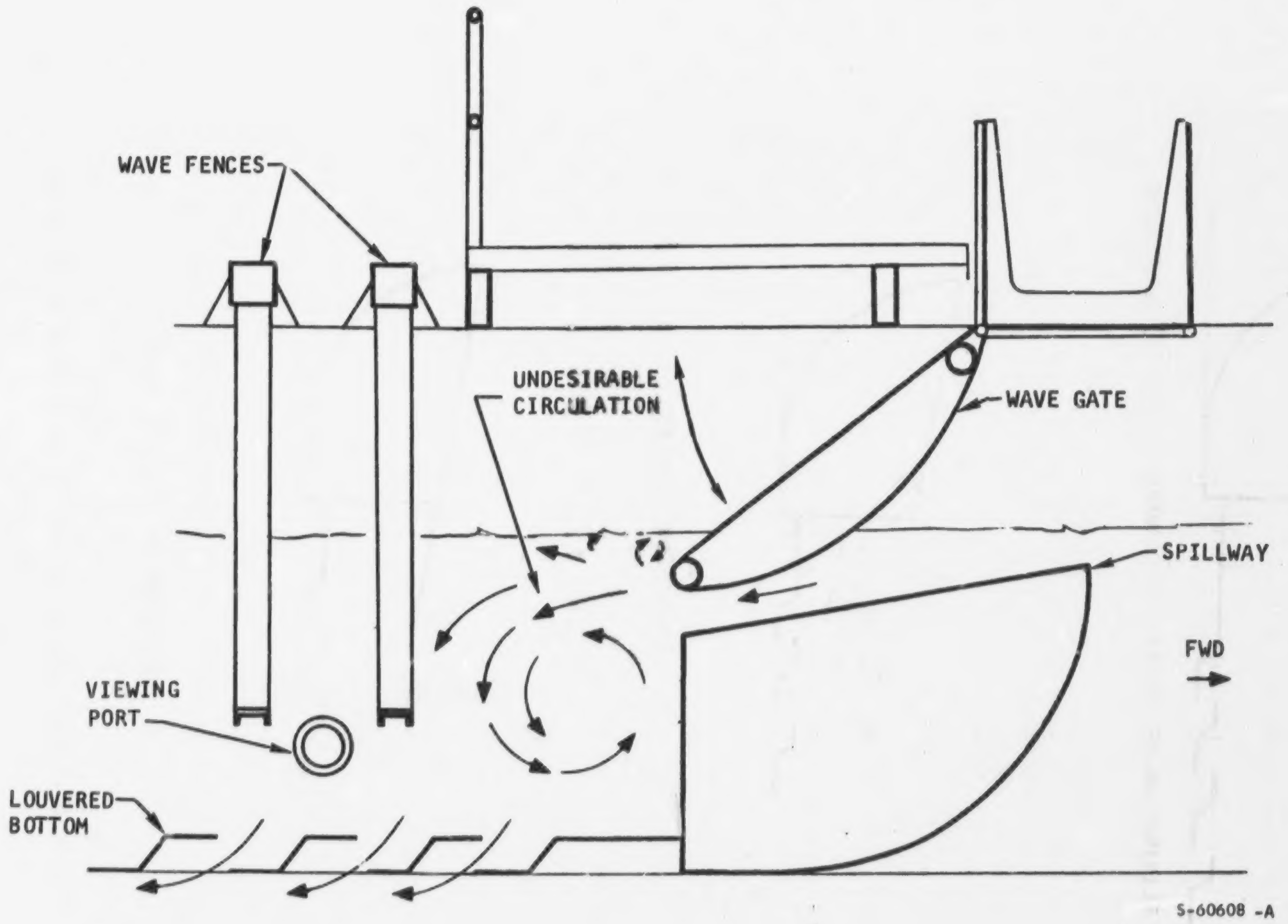
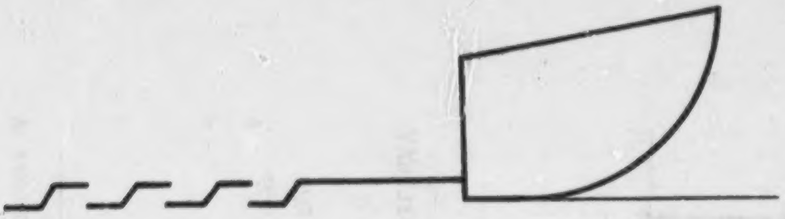
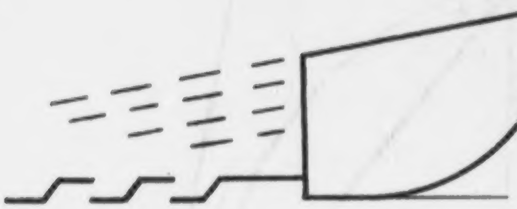


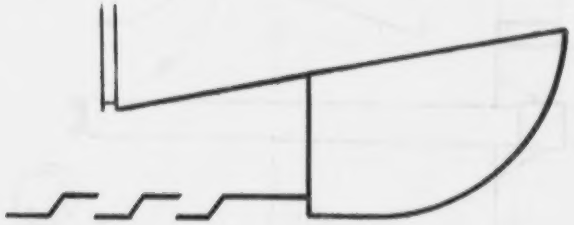
Figure 82. Turbulence at Forward End of Quiet Pond



a. ELIMINATION OF LOUVERS IN FORWARD SECTION OF QUIET POND



b. HORIZONTAL BAFFLES



c. EXTENSION OF SPILLWAY SLOPE

S-60616

Figure 83. Possible Solutions to Quiet Pond Turbulence

CENTRIFUGE

Analysis of Separable Oil Drop Size

A small oil drop entering the annulus of the oil/water centrifuge separator is envisioned to be the same as if it were entering a straight nonrotating channel and under the influence of a high gravitational field equivalent to the centrifugal force produced by rotation of the centrifuge. The following assumptions are made in the analysis.

1. Assumptions

(a) The drops are spherical in shape.

(b) The distance between drops is large enough to assume no interaction between drops (this allows the use of analysis on a single drop).

(c) The drops are not near walls or other boundaries.

(d) The forces acting on the drops are:

Buoyant force due to density difference between the drops and the seawater

The external force which is equivalent to the centrifugal force produced by rotation of the centrifuge

Viscous drag (represented by Stokes' drag law, which requires a Reynolds number < 1) (Figure 84)

(e) All other forces are assumed to be negligible.

2. Initial Conditions

The initial operating conditions considered for this analysis are the following:

(a) The drop enters the centrifuge annulus at time $t = 0$ and has zero radial velocity.

(b) The drop enters the centrifuge annulus at a distance R from the axis of rotation.

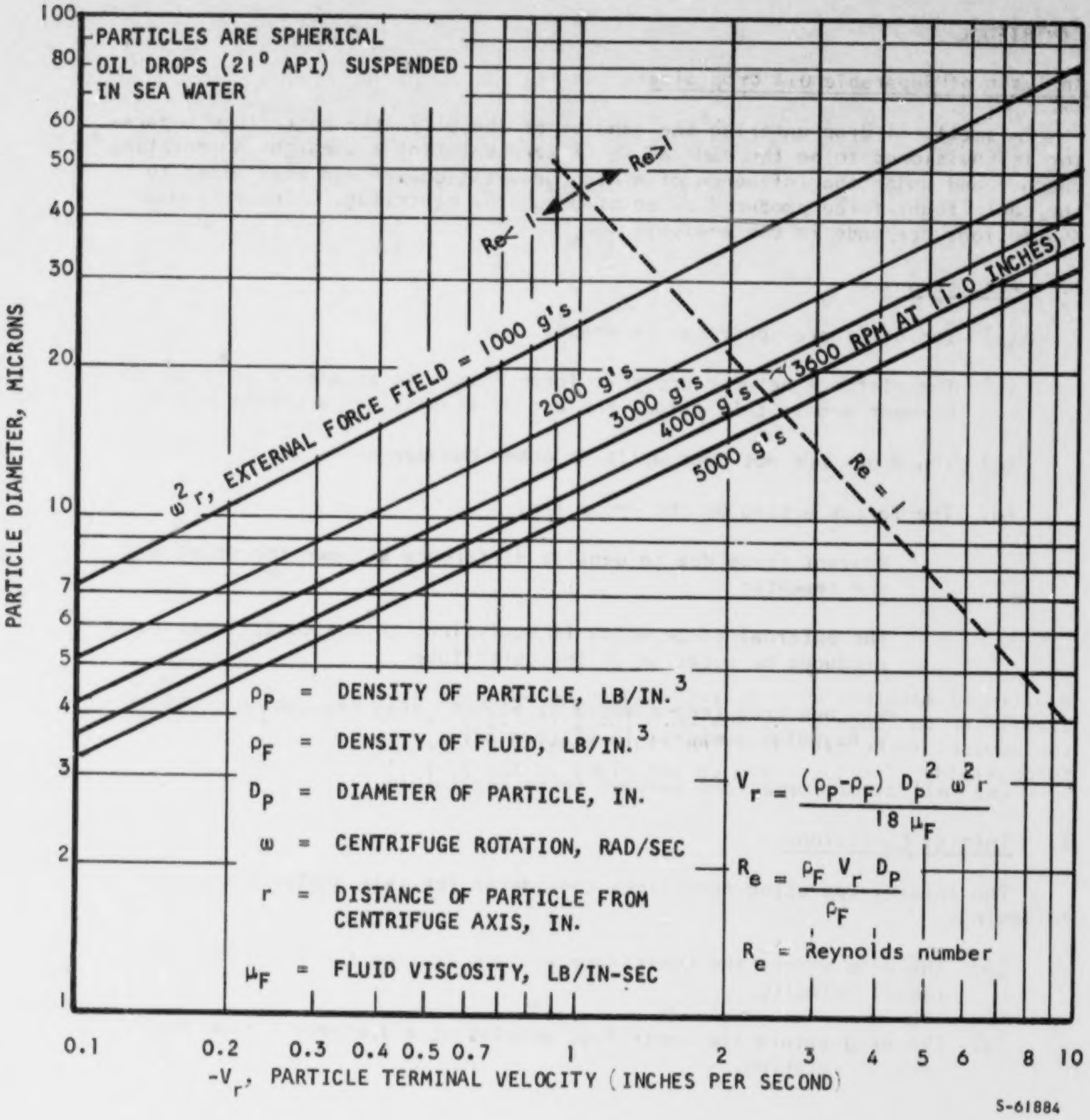


Figure 84. Oil Drop Terminal Velocity as a Function of Drop Diameter and Centrifugal Force

3. Analysis

The equation of motion is:

$$\frac{\pi}{6} D_P^{\,3} \left(\rho_P + \frac{1}{2} \rho_F\right) \frac{d^2 r}{dt^2} = \frac{\pi}{6} D_P^3 \left(\rho_P - \rho_F\right) \omega^2 r - 3\pi\mu_F D_P \frac{dr}{dt}$$

r = radius vector from the centrifuge axis of rotation to the oil drop (the origin moves along the centrifuge axis with the velocity of the suspending fluid)

t = time

D = diameter

ρ = density

ω = angular velocity

μ = viscosity

subscripts P = particle (oil drop)
F = fluid (sea water)

The term on the left-hand side of the equal sign is the inertia force. It is composed of the ordinary inertia plus an additional apparent mass. This additional apparent mass arises because we have applied a Galilean transformation to an unsteady flow problem. The first term on the right-hand side is the buoyant force caused by the fluid density difference in the centrifugal force field. The last term on the right is the Stokes' drag force.

The solution of the equation is:

$$\left(\frac{r}{R}\right) = e^{-\alpha t} \left[\cosh \left(\sqrt{1 + (\beta/\alpha)^2}\ \alpha t\right) + \frac{\sinh \sqrt{1 + (\beta/\alpha)^2}\ \alpha t}{\sqrt{1 + (\beta/\alpha)^2}}\right]$$

$$\left(\frac{v_r}{V_r}\right) = \frac{2\sqrt{1 + (\beta/\alpha)^2}}{\left[1 + \sqrt{1 + (\beta/\alpha)^2}\ \coth \sqrt{1 + (\beta/\alpha)^2}\ \alpha t\right]}$$

$v_r = \frac{dr}{dt}$ = radial velocity

V_r = terminal radial velocity = $\frac{(\rho_P - \rho_F)\, D_P^{\,2} \omega^2 r}{18 \mu_F}$

R = initial radial distance ($r = R$ at $t = 0$)

$$\alpha = \frac{9\mu_F}{D_P^{\,2}\,(\rho_P + \frac{1}{2}\rho_F)}$$

$$\beta = \sqrt{\frac{(\rho_P - \rho_F)}{\left(\rho_P + \frac{1}{2}\rho_F\right)}}\,\omega$$

The solutions to the equation of motion for 21° API oil drops suspended in seawater are presented graphically in Figures 84 through 86. The oil drop residence time in the oil/water centrifuge as a function of oil/water mixture flow rate is shown in Figure 87.

As an example, consider the case where the oil/water mixture flow rate is 500 gpm and the rotational speed is 3600 rpm. With a centrifuge annulus having a 24-in. OD and 20-in. ID and a length of 60 in., the residence time in the centrifuge of an oil drop would be 4.2 sec (from Figure 87).

The centrifugal force at the mean radius of the annulus is 4000 g (Figure 84). Also, it can be seen that Stokes' drag law is not valid for particles larger than approximately 18μ (microns). For an 18μ-particle, the terminal velocity is 2.5 in./sec.

Figure 85 shows that it takes an 18μ-particle approximately 10^{-4} sec to reach 99 percent of its terminal velocity. Smaller particles reach terminal velocity even faster. Thus, for the oil drops being considered here (< 18μ), terminal velocity is attained instantaneously, for all practical purposes.

Figure 86 indicates the particle size that can be separated. For the oil/water separator the parameter $[(R-r)/R]$ is equal to 1/6 and the residence time in the centrifuge is 4.2 sec. Ideally, at 3600 rpm all oil drops larger than 8μ can be separated. In actual practice, this drop size will be somewhat larger because of the influence of the adjacent particles and the walls.

Droplet Size Measurement

1. The Counter

The theoretical predictions of separator efficiency can be utilized only if the actual size of the oil droplets present in the emulsion is known. There are several well-established methods for measuring drop size but the methods that afford the highest accuracy and the highest degree of automation are those based on photoelectric optical systems.

An HIAC-SS Automatic Particle Counter, made by High Accuracy Products, Claremont, California, was used during land test. No droplet measurements were made at sea or on samples recovered at sea. The counter schematic diagram is shown in Figure 88. A sample of the oil/water emulsion flows through a small rectangular fluid passage and past a window. Oil particles in the fluid pass by

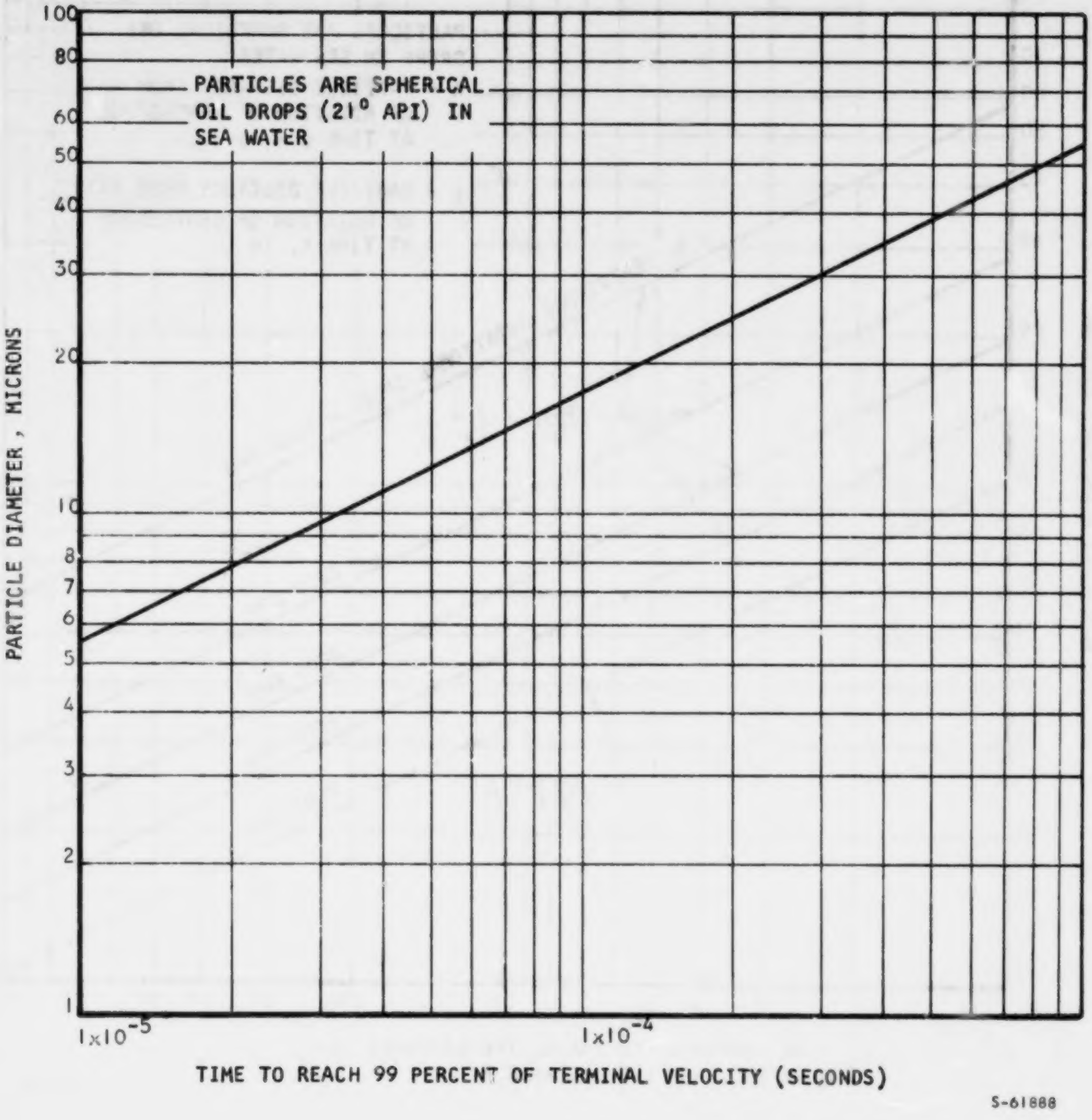


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Figure 85. Time Required for an Oil Drop to Reach 99 Percent of Terminal Velocity

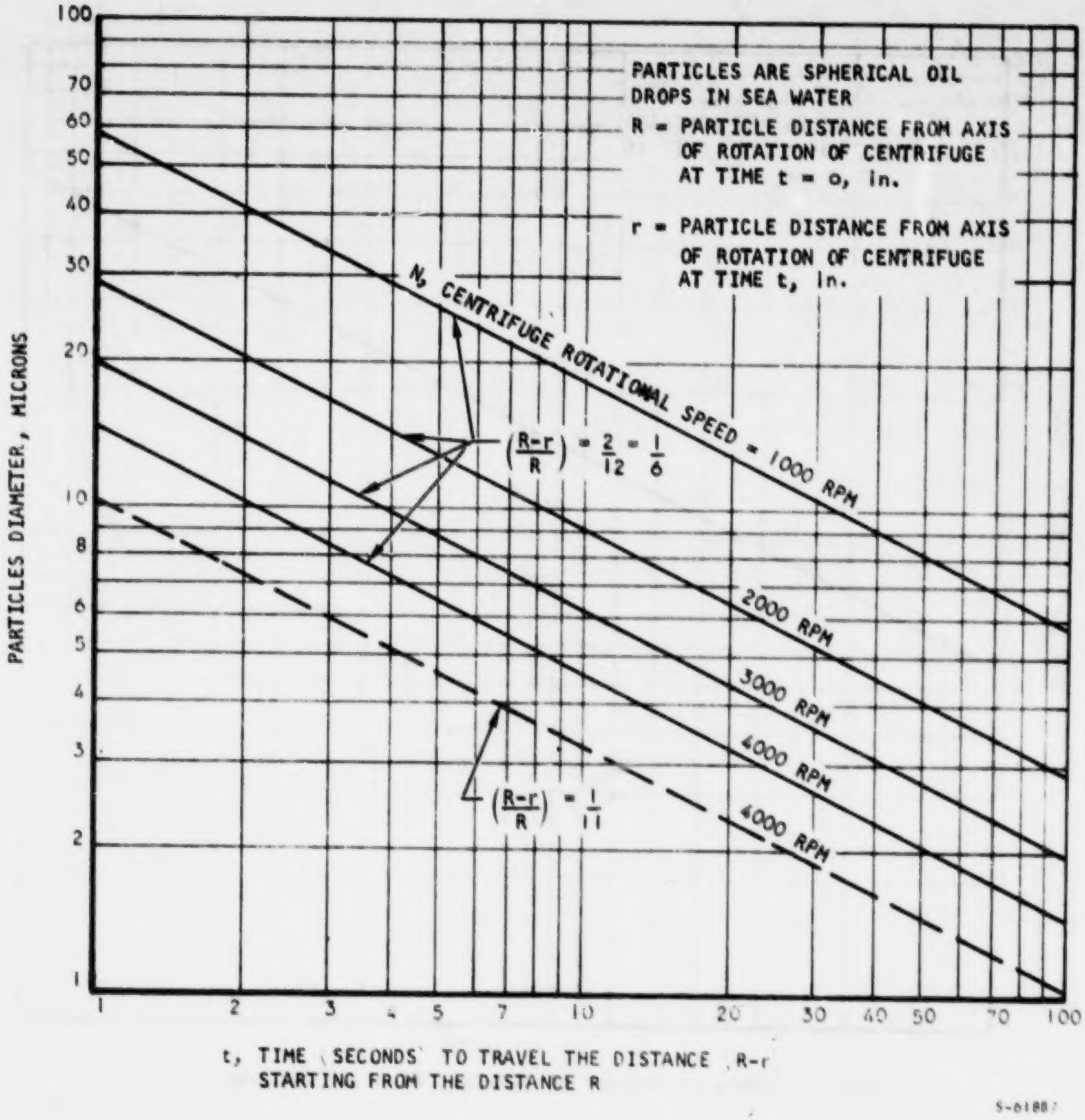

Figure 86. Travel Time as a Function of Drop Diameter and Rotational Speed

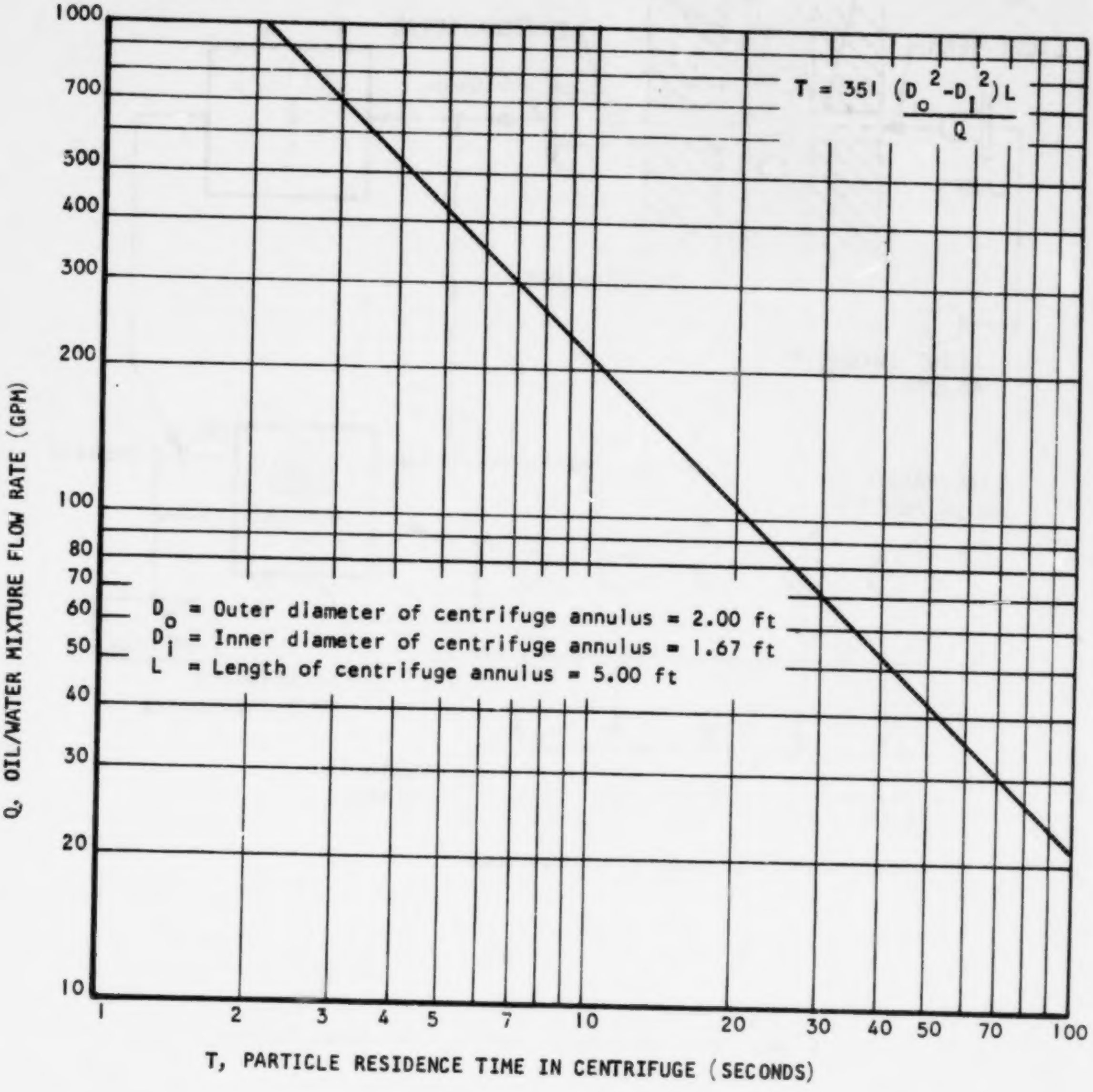

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Figure 87. Oil/Water Centrifuge Oil Drop Residence Time as a Function of Flow

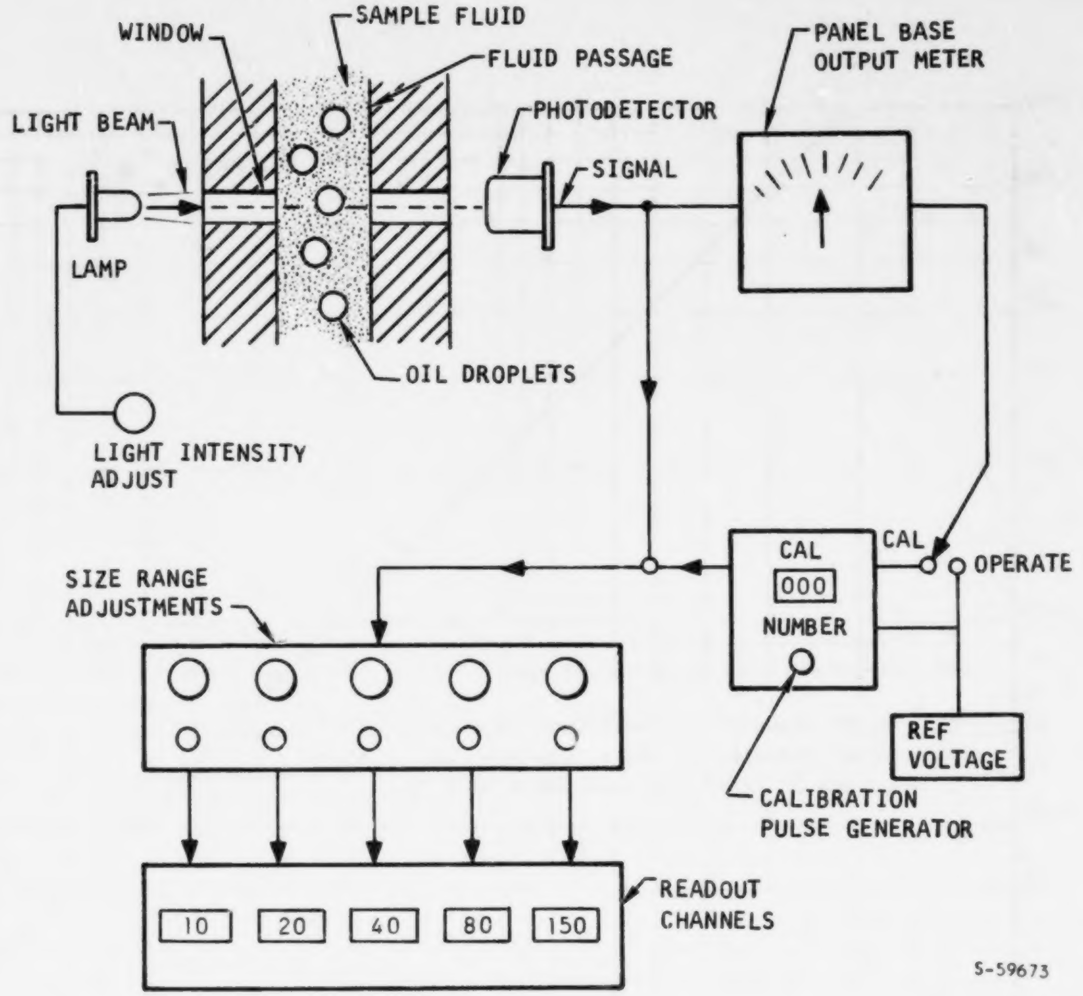

Figure 89. Photoelectric Particle Counter Schematic

the window one by one. Light from a tungsten lamp is formed by the window to a parallel beam of an exact size, and directed onto a photodetector. Using the Light Intensity Adjust the operator establishes the proper base voltage from the photodetector (as indicated on the Panel Base Output Meter). Each particle, as it passes the window, interrupts a portion of the light beam according to its size. This causes a specific reduction (or pulse) in the voltage that is proportional to the size of the particle as long as specified limits of particle concentration are not exceeded. Five counting circuits (channels) with preset thresholds tally the particles by size. A Size Range Adjustment is provided for each channel to permit the operator to select any desired size ranges. A built-in Calibration Pulse Generator provides the operator with reference pulses to simulate any particle size for adjusting and verifying the size ranges.

Accurate sizing is obtained regardless of the color or shape characteristics of the particles. Adjustment of light intensity by the operator immediately corrects for the optical density of any fluid and also for any deposits on the window (with no change in calibration settings required). If two particles are in the sensing zone at the same time, their areas are summed and reported as one large particle. This will not occur if concentration limits recommended by the manufacturer are followed. Initial tests on oil-water samples at the manufacturer's laboratory also showed that the counter becomes saturated if the recommended particle concentration is markedly exceeded. Under these conditions it is necessary to dilute the sample until the particle concentration is below the recommended limits.

2. Initial Testing

The oil droplet measurement program was conducted at the Signal Oil Company lease in Huntington Beach, California. In order to simulate the Sea Dragon operating conditions, the centrifuge was run on salt water mixed with various proportions of various oils. This water is obtained from a well containing seawater that has percolated through the ground from the nearby sea. The well water contains particulate matter and it is essential to determine its size distribution since this forms a background count that, if significant, must be subtracted from the overall count to give the oil size distribution. Samples of the well water were taken in bottles at the well outlet. It was found that the suspended particulates (an iron salt complex) were photosensitive and broke down in the sunlight to give a black coloration to the water. Table 8 gives the results of these tests.

An examination of Table 8 shows that the number of particles in a well water sample decreases the longer the water is allowed to stand before counting. This is quite consistent with the sedimentation of the particles since a 5μ-diameter particle with a specific gravity of 3.0 has a terminal velocity of about 0.0001 fps in water, and so would fall about 1 in. in 15 min. A correction, therefore, should be made for this background count. If the well water has passed through either a centrifugal pump or the centrifuge, however, then the majority of these particles will have been precipitated, since the centrifugal force in water on a particle with a specific gravity of 3.0 is 20 times that on a similar sized particle with a specific gravity of 0.9 (typical value of oil).

TABLE 8

EFFECT OF TIME ON PARTICLE COUNTS IN WELL WATER, MAY 14, 1970

Test No.	Volume Sampled	Number Particles					Comments
		5 μ	10 μ	20 μ	40 μ	80 μ	
A1	10 cc	5801	2051	748	150	17	Counted at once, water clear.
A2	10 cc	5819	2392	763	166	21	
B1	10 cc	4583	1096	269	29	2	Counted after 5 min, water clear to grey
B2	10 cc	4852	1105	202	27	2	
B3	10 cc	4371	1046	202	40	8	
C1	10 cc	3849	445	80	8	0	Counted after 15 min, water black
C2	10 cc	4483	416	52	1	0	

Trial tests using samples of oil-water emulsion showed that the recommended number of particles per unit volume sampled was usually exceeded except for the lowest oil concentrations. It was necessary, therefore, to arrange for a method of diluting the sample in order to reduce the particle concentration.

4. Test Arrangements

The arrangement finally used is shown schematically in Figure 89. Samples, of the oil-water emulsion may be taken at one of three stations by pitot-type probes inserted into pipe lines at entry to the centrifugal pump, at entry to the centrifuge, and at exit from the centrifuge. The emulsion passes through a flowmeter to a mixing section where filtered seawater is added and the mixture then passes to the particle counter. The seawater is supplied from a pressurized storage tank, and passes through a 5μ absolute filter and a flowmeter before mixing with the emulsion. Thus by suitable adjustment of the control valves the emulsion can be diluted in any required ratio and control gained over the particle concentration as seen by the counter. The possibility that the absolute filter was not absolute was checked by passing the dilutant alone through the counter. The results are shown in Table 9.

Background count due to the dilutant is negligible and the steady decline in number or particles with time suggests that the particles recorded were actually those already in the lines downstream of the filter and dislodged at startup.

In order to determine the effect of centrifuge rotation on the iron salt particles in the well water, samples were taken downstream of the centrifuge pump (i.e. at entry to the centrifuge) and at exit from the centrifuge. The results are shown in Table 10.

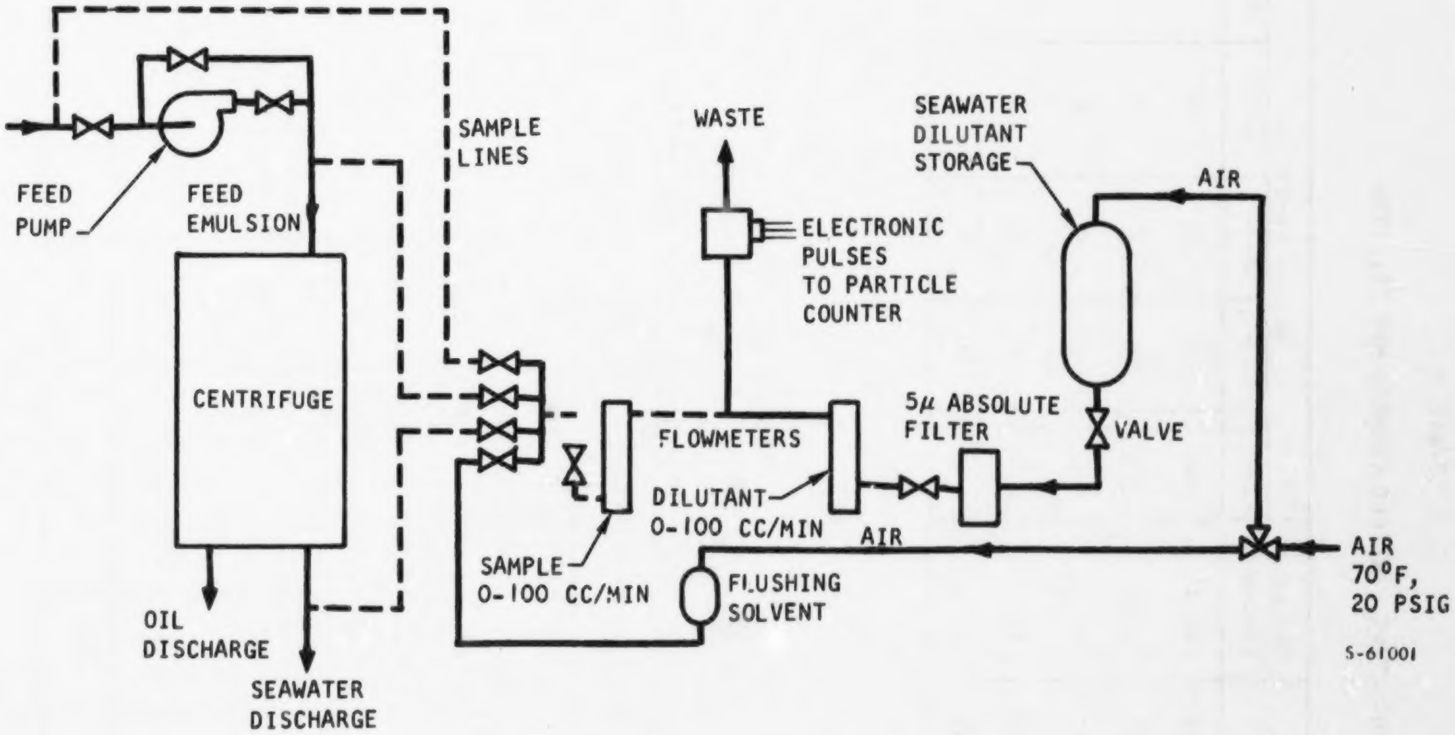

Figure 89. Schematic of the Particle Sampling System

TABLE 9

DILUTANT PARTICLE COUNTS, MAY 25, 1970

Test No.	Time, Hrs	Volume Sampled	Number Particles				
			5 μ	10 μ	20 μ	40 μ	80 μ
D1	13.55	44 cc	226	17	2	0	0
D2	13.56	44 cc	112	8	2	0	0
D3	13.57	44 cc	51	3	0	0	0
D4	13.58	44 cc	46	4	1	0	0
D5	13.59	44 cc	36	3	0	0	1

TABLE 10

WELL WATER PARTICLE COUNTS, MAY 26, 1970

Test No.	Volume Sampled	Number Particles					Comments
		5 μ	10 μ	20 μ	40 μ	80 μ	
E1	100 cc	30223	26023	15476	760	8	Downstream of pump; flow rate 107 gpm
E2	100 cc	30927	25012	13652	574	3	
E3	100 cc	32766	26197	14837	662	2	
F1	100 cc	28316	27829	14830	580	12	Downstream of pump; flow rate 225 gpm
F2	100 cc	27953	27648	15582	674	4	
F3	100 cc	28482	27680	15470	713	6	
G1	50 cc	1725	4820	8189	11186	8773	Downstream of centrifuge; flow rate 225 gpm; centrifuge speed 1750 rpm.
G2	50 cc	1910	5273	8934	12607	8680	
G3	50 cc	1757	5002	8819	11833	8569	
H1	0	1520	0	0	0	0	

Tests E and F were made at entry to the centrifuge. The effect of water flow rate is very small, as the number of particles in suspension remains virtually unchanged as the flow rate is more than doubled. Particle deposition in the centrifugal pump is small when compared with the results in Table 8. (The number of particles in tests E and F should be divided by ten for a direct comparison with Table 8, since the volume sampled is ten times greater.)

The particle counts at exit from the centrifuge (test G) show an extraordinary increase in the number of large particles instead of the expected decrease. This was eventually found to be caused by gas bubbles whose origin was a pressurized nitrogen blanket on the source well that prevented entrance of oxygen into the injection system. By extending the length of line between the sample collection point and the counter, coalescence of these bubbles was encouraged so that they collected on the pipe walls and did not pass through the counter.

Test H revealed another cause of spurious readings. The vibrations transmitted from the centrifuge to the counter caused the illuminating lamp filament to vibrate; these intensity fluctuations were seen by the photodetector as small particles. This effect is masked when there is flow through the counter but under no-flow conditions the effect is evident. The lengthening of the connecting line between the collection pitot and the counter (in order to allow the bubbles to coalescence) also served to isolate the counter from these vibrations. Further check tests with this modification showed that the background count due to well water particulates at the centrifuge exit was essentially negligible.

4. Data Reduction

It is simple but tedious to calculate the mg/l of oil present in a given volume of emulsion if the number and size of all the oil particles are known. The particle counter, however, does not give the exact size of each particle but instead gives the number of particles in a given size range. Thus, an average value of the size range has to be chosen in order to evaluate the volume of oil. The usual average is the arithmetic mean diameter, which is given by $(D_1 + D_2)/2$ where D_1 and D_2 are the upper and lower diameters in the range. For a uniformly distributed population of droplets, the use of this average is in error since larger droplets make a much greater contribution to the total volume than do an equal number of smaller ones. The correct average to use is the volumetric mean diameter, which is given by $\left[(D_1^3 + D_2^3)/2\right]^{1/3}$ since this biases the average toward the upper limit.

A small program was written in FORTRAN 4 to evaluate the concentration of oil in the emulsion from an input of the size ranges, the number of drops in each range, and the total volume sampled. The program is listed in Figure 90.

```
C   PROGRAM FOR ANALYSIS OF OIL-WATER COMPOSITION DATA
C
C   WRITTEN BY HERBERT N. ROSENBERG / AIRESEARCH-LOS ANGELES
C
      REAL N(5)
      DIMENSION TITLE(20),DAM(5),DVM(5),VAM(5),VVM(5),FAM(5),FVM(5),
     1 NI(5),DL(5),DH(5)
 1000 READ(5,5000,END=9999) TITLE
 5000 FORMAT(20A4)
      READ(5,5001) N, VTOT
 5001 FORMAT(6F10.0)
      READ(5,5002)  (DL(I),DH(I), I=1,5)
 5002 FORMAT(8F10.0)
      PI=3.14159
      DO 100 I=1,5
      DAM(I)=(DL(I) + DH(I))/2.0
      DVM(I)=((DL(I)**3 + DH(I)**3)/2.0)**0.33333
      VAM(I)=PI*DAM(I)**3*N(I)/6.0
  100 VVM(I)=PI*DVM(I)**3*N(I)/6.0
      VSAM=0.0
      VSVM=0.0
      DO 110 J=1,5
      VSAM=VSAM + DAM(J)**3*N(J)*PI/6.0
  110 VSVM=VSVM + DVM(J)**3*N(J)*PI/6.0
      DO 120 I=1,5
      FAM(I)=(DAM(I)**3*N(I)*PI*100.0/6.0)/VSAM
  120 FVM(I)=(DVM(I)**3*N(I)*PI*100.0/6.0)/VSVM
      CAM=VSAM/(VTOT*1.E6)
      CVM=VSVM/(VTOT*1.E6)
      SUMN=0.0
      SNDAM=0.0
      SNDVM=0.0
      DO 130 J=1,5
      SUMN=SUMN + N(J)
      SNDAM=SNDAM + N(J)*DAM(J)
      SNDVM=SNDVM + N(J)*DVM(J)
  130 CONTINUE
      SNDAM3= VSAM*6.0/PI
      SNDVM3= VSVM*6.0/PI
      DAAM= SNDAM/SUMN
      DAVM= SNDVM/SUMN
      DVAM= (SNDAM3/SUMN)**0.33333
      DVVM= (SNDVM3/SUMN)**0.33333
      WRITE(6,6000)  TITLE
 6000 FORMAT(1H1/////,15X,'TEST IDENTIFICATION    ',20A4)
      WRITE(6,6001) VTOT
 6001 FORMAT(/1H0,15X,'SAMPLE VOLUME IS',F7.2,2X,'CUBIC CENTIMETERS')
      DO 200 I=1,5
  200 NI(I)=N(I)
      WRITE(6,6002) (DL(I),DH(I), I=1,5)
 6002 FORMAT(///,1H0,'SIZE RANGE, MICRONS          ',5(F5.1,'-',F5.1,5X))
      WRITE(6,6003) (NI(I), I=1,5)
 6003 FORMAT(1H0,    'NUMBER OF DROPS              ',5(I8,8X))
      WRITE(6,6004)  (FAM(I), I=1,5)
 6004 FORMAT(1H0,    'PCT VOLUME(ARITH. MEAN)      ',5(F8.2,8X))
      WRITE(6,6005) (FVM(I), I=1,5)
 6005 FORMAT(1H0,    'PCT VOLUME(VOL. MEAN)        ',5(F8.2,8X))
      WRITE(6,6006) CAM
 6006 FORMAT(///,1H0,20X,'OIL-WATER PPM(ARITH. MEAN)               ',F8.1)
      WRITE(6,6007) CVM
 6007 FORMAT(1H0,20X,    'OIL-WATER PPM(VOL. MEAN)                 ',F8.1)
      WRITE(6,6008) DAAM
 6008 FORMAT(1H0,20X,    'MEAN DIA(ARITH. MEAN), MICRONS           ',F8.1)
 6009 FORMAT(1H0,20X,    'MEAN DIA(VOL. MEAN), MICRONS             ',F8.1)
 6010 FORMAT(1H0,20X,    'VOL. DIA(ARITH. MEAN), MICRONS           ',F8.1)
 6011 FORMAT(1H0,20X,    'VOL. DIA(VOL. MEAN), MICRONS             ',F8.1)
      WRITE(6,6009) DAVM
      WRITE(6,6010) DVAM
      WRITE(6,6011) DVVM
      GO TO 1000
 9999 STOP
      END
```

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Figure 90. Data Reduction Program

The program essentially calculates the oil-in-water concentration in mg/l and is based on the volumetric mean diameter of each size range. It also calculates what percentage the drops in each size band contribute to the total volume, as well as two overall mean diameters that can be used to typify the distributions. For comparison purposes the program also calculates these values based on the arithmetic mean diameter of each size range.

Typical program outputs are shown in Figure 91.

5. Results

The particle counter was used on some of the centrifuge tests in order to try to understand the basic mechanisms governing centrifuge performance. Table 11 gives the recorded data and the computed results for oil concentration and volumetric mean diameter for a series of tests on the oil-containing waste water discharge from the settling tanks used on the Signal Oil Company Lease.

Runs 1 to 5 are taken at the outlet from the centrifuge under conditions as steady as it was possible to maintain. The waste water system was not under direct control and certain results should be discarded because of suspected system transients; for example, run 2.

Runs 7 to 12 are taken at the inlet to the centrifuge. The effectiveness of the centrifuge in reducing the oil concentration and also in mean particle diameter can be seen. Morever what is really significant is the fact that there are considerably more particles per cc in the 5- to 10μ-range at exit from the centrifuge than at entry. This indicates the existence of some powerful droplet-shearing mechanism in the centrifuge. In runs 1 to 12, the centrifugal pump was bypassed, as the waste water inlet pressure was sufficient. In runs 15 to 18, although the pressure was the same, the centrifugal pump was run and throttled to give the same flow rate. The effect was a considerable reduction of the number of large particles, indicating that the pump exerts a shearing action on the oil resulting in smaller particles that are more difficult to separate.

The next series of tests, still using the oil-bearing waste water discharge, was designed to determine the effect of emulsion flow rate on the performance of the centrifuge since the particle residence time in the centrifuge is reduced directly as the flow rate increases. The results are given in Table 12.

There is a small but discernible increase in the exit oil concentation as the throughput emulsion flow rate increases.

A significant result is the presence of large oil particles at exit from the centrifuge. The calculations outlined in previous paragraphs indicate that no 40-μ particles should be able to pass through the centrifuge at these flow rates (residence times) and rotational speeds, especially when the inlet emulsion has such a relatively low oil concentration. The inlet emulsion oil concentration was less than 5000 mg/l, and this amount should not be sufficient to induce hindered settling.

Test Identification   Test June 2, 1970 Run 2   Outlet

Sample Volume is 20.00 Cubic Centimeters

Size range, microns	5.0 to 10.0	10.0 to 20.0	20.0 to 40.0	40.0 to 80.0	80.0 to 150.0
Number of drops	79,847	35,345	3,534	543	108
Pct volume (arith. mean)	6.36	22.51	18.01	22.13	31.00
Pct volume (vol. mean)	6.44	22.80	18.24	22.42	30.09

Oil-water mg/l (arith. mean)	13.9
Oil-water mg/l (vol. mean)	18.3
Mean dia (arith. mean) microns	10.7
Mean dia (vol. mean) microns	11.8

Measured Values

Discharge oil 16 mg/l

Inlet oil 47 mg/l

Test Identification   Test June 2, 1970 Run 11   Inlet

Sample Volume is 20.30 Cubic Centimeters

Size range, microns	5.0 to 10.0	10.0 to 20.0	20.0 to 40.0	40.0 to 80.0	80.0 to 150.0
Number of drops	25,073	31,333	15,475	3,952	185
Pct volume (arith. mean)	0.63	6.34	25.03	51.14	16.86
Pct volume (vol. mean)	0.64	6.38	25.21	51.50	16.27

Oil-water mg/l (arith. mean)	43.1
Oil-water mg/l (vol. mean)	57.0
Mean dia (arith. mean) microns	18.2
Mean dia (vol. mean) microns	20.0

Measured Values

Inlet oil 42 mg/l

Discharge oil 19 mg/l

Figure 91. Sample Performance Test Data

TABLE II

WASTE WATER DROPLET COUNTS, JUNE 2, 1970

Run	Volume Sampled	Number of Particles					PPM	Mean Diameter	Comments
		5 µ	10 µ	20 µ	40 µ	80 µ			
1	20.0	75210	14390	1118	186	65	8.6	15.3	Sampling at centrifuge outlet, centrifuge speed is 1770 rpm, flow rate is 194 gpm. Centrifugal pump off.
2	20.0	79487	35345	3534	543	108	18.3	18.0	
3	21.0	50826	42208	4199	265	5	11.4	16.7	
4	21.0	47775	41212	3122	116	15	9.7	16.1	
5	17.3	43516	37856	2892	121	3	10.3	15.9	
7	24.0	27959	36447	17732	5004	130	54.8	30.6	Sampling at centrifuge inlet; conditions as above. All testing done on waste water discharge
8	24.1	20063	28860	19284	8329	370	85.9	37.2	
9	24.0	22767	31123	18137	5342	485	71.7	31.8	
10	24.0	23107	35157	17472	4866	320	61.6	32.7	
11	20.3	25073	31333	15475	3952	185	57.0	30.7	
12	20.0	24709	30265	14249	3360	168	51.2	30.0	
15	23.3	30193	40108	19645	2400	11	36.7	26.1	Sampling at centrifuge inlet; conditions as above except pump turned on 950 rpm
16	20.6	28993	38889	18804	2284	8	39.2	25.9	
17	20.6	27877	36999	18579	2308	10	39.0	26.2	
18	21.0	27523	36482	18660	2021	28	41.4	26.9	

TABLE 12

EFFECT OF FLOW RATE ON EXIT OIL CONCENTRATION, JUNE 2, 1970

Run	Diameter	Number of Particles					mg/l	Mean Diameter	Comment
		5 μ	10 μ	20 μ	40 μ	80 μ			
28	27.0	55906	3176	1123	208	11	3.2	14.0	Centrifuge outlet, 2750 rpm, flow rate 110 gpm
29	27.0	61118	2202	672	98	4	2.0	11.8	
30	26.6	52654	3551	1686	410	14	5.0	16.3	
							(3.4)*		
31	30.0	57074	46670	2402	74	1	6.1	14.9	As above but flow rate 194 gpm
32	29.0	73829	24460	516	23	1	3.2	12.2	
33	29.0	71914	17493	1146	144	26	4.6	14.1	
							(4.6)*		
45	29.0	67143	19614	975	120	1	3.6	13.1	As above but flow rate 320 gpm
46	29.0	66347	26034	1586	216	5	5.2	14.4	
47	29.0	65352	26989	1676	368	9	6.2	15.4	
49	29.3	66620	30190	1296	175	1	4.9	14.0	
							(5.0)*		

*Average exit oil concentration

Conclusions and Recommendations

More tests were made using the particle counter; they merely substantiated the two main observations, namely (1) the centrifuge failed to remove all the large oil particles and (2) there were more small particles leaving the centrifuge than entering it.

In order to explain these results, the initial design **assumptions were** examined more closely. Stokes' Law assumes that the particle is alone and falls through a fluid of infinite extent; that is, the flow field around the particle is not affected by neighboring particles or containing walls. In reality when there are many particles close together, the cloud of particles falls as though it were a solid body of the same diameter as the cloud with the average density of the oil and water. It therefore falls far faster than would the individual particles that comprise it. If, however, the cloud extends close to the containing walls, the liquid that is displaced as the cloud falls is prevented from freely circulating and has to percolate back through the cloud. The closer the particles are together, the more significant this effect becomes. Thus, if 5-percent oil is present and distributed uniformly as equally sized droplets, the distance between particles is only 1.3 particle diameters, and the whole cloud falls at 53 percent of the velocity of a single isolated particle. This effect therefore impairs the operation of the centrifuge, but it is not enough to explain the presence of the largest droplets in the outlet.

It is also assumed that the liquid flowed through the centrifuge without rotational slip. This is true in bowl centrifuges, but here the absence of liquid prerotation, together with high flow rates, combine to produce a secondary flow vortex. These coriolis force-induced vortexes exist in each flow passage and rotate with respect to the guide vanes in the opposite direction to the main rotation. As the fluid flows axially through each flow passage, it rotates about its own axis as well as about the centrifuge axis. The centrifugal force acting on the oil particles is different from that if the liquid rotated as a solid body. The net result is to reduce the effective centrifugal force. Calculations for this particular centrifuge geometry showed that this centrifugal force reduction only amounts to about 10 percent and thus is not sufficient to explain the oil carryover.

The mean axial velocity of the water through the centrifuge is not large enough to re-entrain any oil from the surface of the inner barrel nor has the velocity any radial component. The tangential velocity of the induced vortex, however, is as high as 30 fps and it is directed radially outwards, with respect to the centrifuge axis, for part of each revolution made by the vortex. The re-entrainment of oil already deposited on the inner barrel is particularly likely where the oil film is thickest. Any devices that reduce this thickness may be expected to benefit the operation of the centrifuge. This reduction may be accomplished either by increasing its velocity or by removing some (or all) of the oil.

A conical inner barrel would cause the oil to flow very rapidly towards the exit weir under the influence of the centrifugal force component directed along its surface. This rapidly flowing oil film is much thinner than the cylindrical barrel film and resists re-entrainment. This probably explains why the separation efficiency using hot emulsion is so high. The reduced viscosity of the oil film allows faster and hence thinner flow.

The alternative is to remove the oil as soon as it is deposited. This may be achieved by using more than one removal weir. This concept of oil removal may also be achieved using a porous shield positioned around the inner barrel. This shield is effectively an infinite number of stages. The oil passes through the shield under the influence of the centrifugal force and is shielded from the re-entraining effects of the vortex swirl. The oil now flows axially along the annulus between the inner barrel and the shield towards the exit weir. The final configuration must await the results of further analysis and tests.

ECONOMICS OF OPERATION

Ocean Oil Spill Recovery with a Skimming System

In an oil skimming system of large capacity, the cost of recovery per barrel of oil is quite dependent upon the recovery rate. This is as opposed to sorbent, sinking, or dispersant systems in which the total cost is more dependent upon the quantity of oil recovered due to purchase and handling of the active materials used. These costs have been estimated as follows for a 200 bbl/hr spill:

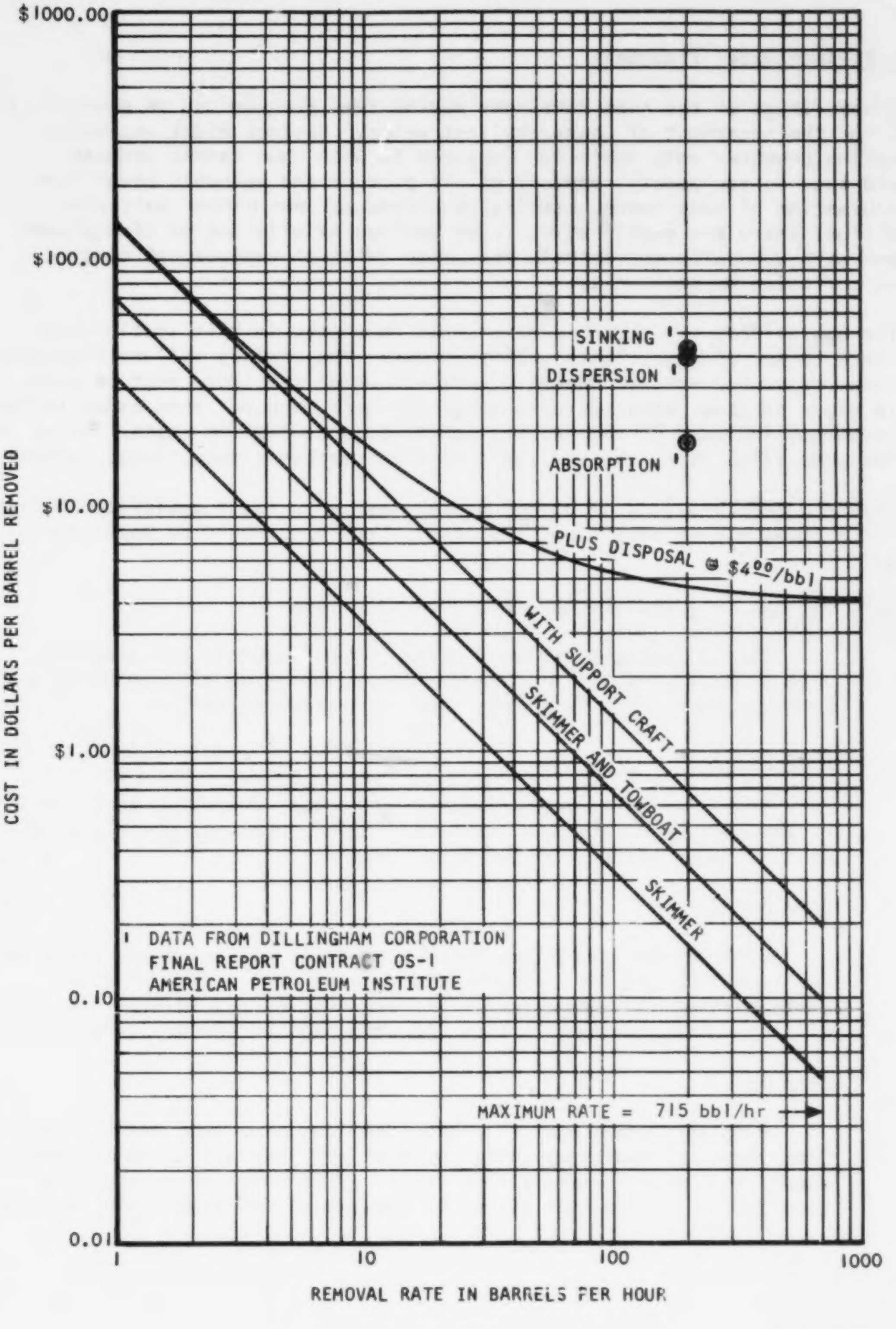
Sorbent (straw)	$18/bbl recovered
Sinking (chalk)	$44/bbl recovered
Dispersant	$40/bbl recovered

The cost for recovery of oil by means of the skimming system described in this report is shown in Figure 92. The lowest cost curve is for the recovery of oil from the water surface on a 24-hr/day basis considering skimmer operation only. Such an operation might occur where the oil spill is contained by booms or other restraints and the oil is being carried to the skimmer by the wind or water currents. The second curve shows the cost if the system also involves a towboat and an oil boom. The third line shows cost of the entire operation supported at sea by an additional boat that would provide accommodations and meals for the alternate crews, and storage facilities for oil recovered (up to 2000 bbl). The uppermost curve includes the cost of disposing of the recovered oil assuming that it must be transported to shore by barge, offloaded into vacuum or tank trucks, transported to a disposal site, and disposed of by burial. These costs per barrel were estimated as follows:

Barge transport to shore and unloading	$1.00
Truck transport	2.00
Disposal	1.00
	$4.00

Thus, for any significant recovery rate, the cost of transport and disposal of the oil is the principal cost.

Also plotted on Figure 92 are the costs for sorbent, sinking, and dispersal methods as estimated by the Dillingham Corporation and reported in their Final Report, Contract OS-1, with the American Petroleum Institute.



S-65059

Figure 92. Cost of Removing Oil from Ocean Surface

Tanker Ballast Water Treatment

A centrifuge of the type developed during this program may be economically useful for the treatment of tanker ballast water. Savings might accrue by eliminating unwanted ship operation required to wash down tanks; reduced wear and tear on equipment; recovery of oil product and valuable cargo space; and elimination of slop tanks, heating requirements, and harbor pollution. In addition, there are such indirect cost savings as elimination of equipment for tank wash-down plus appreciable reduction in steel replacement costs due to less corrosion on tank walls.

The operational and economic data shown tabulated in this section are based on a tanker of approximately 200,000 dwt. The various ballast treatment techniques presented are not meant to indicate which procedure must be used, but are given to show magnitude of savings for each method. When added to the many items not included in the savings column such as heating costs, increased transfer pump life, etc., the savings projected represent exceptional values.

This economic analysis is based upon the use of a fully qualified 2000-gpm unit; if a 500-gpm unit were used, the centrifuge costs would be approximately doubled.

(a) Method I - Butterworth Method with Slop Tanks

The following example is given for a "load-on-top" practice with a normal routine of cleaning tanks for clean ballast using a 2000-gpm centrifuge for final slop tank clean-up only.

Step No. 1

Clean in rotation approximately one-half the cargo compartments of the ship using Butterworth method. This puts approximately 3000 tons of dirty wash water into the slop tanks.

Step No. 2

Fill appropriate clean tanks with clean ballast water while at the same time draining off the clean lower part of the original dirty ballast (dirty ballast will have settled out so that the oil will be in the top few feet of the water in the ballast compartment).

Step No. 3

Pump dirty portion of original ballast plus wash water (collected from cleaning remaining tanks in rotation) into a slop tank (total capacity is approximately 7000 tons). This waste water contains from 300 to 800 tons of oil or an average of 550 tons (4000 barrels).

Step No. 4

Two 2000-gpm centrifuge separators can process 4000 gpm or approximately 1000 tons per hour. This allows the dirty water to be processed in 6 to 8 hours. Only the clean water-free oil will be retained onboard for load-on-top or fuel as the purified water will be pumped overboard.

A cost summary for this method is shown in Table 13.

(b) Method II - Straight Separation of Settled Ballast Water

An alternate method of using a 2000-gpm centrifuge is presented below.

Load ballast at discharge port and proceed to loading port. During the voyage, the dirty ballast will settle out and all but the top few feet can be discharged while loading. The top few feet can be discharged through the centrifuge separator at a rate of 2000 gpm per separator or approximately 500 tons per hour per separator. In a 200,000-dwt tanker this last dirty ballast portion will be approximately 10 percent of the total ballast water or 10,000 tons. This can be discharged in 6 to 8 hr using 3 centrifuge separators.

The savings and costs between direct and indirect are somewhat different in this case than in the normal load-on-top case. Indirect costs in steel replacement, savings-in-washing costs, including use of equipment, labor, etc., plus the savings in product, etc., are a few samples. Although less oil is reclaimed because only the oil in the tanks filled with ballast (100,000 tons) is processed, large savings are realized by eliminating the slop tanks. A cost summary for this method is shown in Table 14.

(c) Method III - Straight-Through Separation All Ballast Water

The ability to directly process ballast water through the centrifuge while simultaneously loading crude oil in the harbor eliminates the necessity of washing down the tanks during the voyage and therefore the need for slop tanks. Method II, however, assumes that settling between the oil emulsion and seawater takes place in the ballast tanks.

This may not be a good assumption, especially for short duration runs. It is possible that all the ballast water (100,000 tons) must be processed. If such is the case, a longer period of time and more centrifuge units would be necessary. Assuming a 25-hour processing period, eight 2000-gpm centrifuge units (500 tons per hour each) would be necessary to process 100,000 tons of ballast water. A cost summary for Method III is given in Table 15.

TABLE 13

COST SUMMARY - METHOD I

Costs	Savings
Installation Costs 2 units at $100,000 = $200,000 (approximate)* $200,000 at 9 percent interest for 5-yr payoff = $51,300/yr Fuel Costs Each unit requires approximately 100 hp; using an SFC of 0.4 lb/hp-hr, each unit uses 40 lb (~6 gal)/hr of operation. At $0.15/gal, cost per unit is $0.90/hr Total operation per trip = 7 hr per unit Cost per trip = $12.50 Based on a round trip of 10 days or 30 trips/yr, Cost of fuel = $ 375/yr Maintenance Costs Includes periodic inspection and spare parts = $ 3,000/yr	Reclaimed oil 550 tons = 4000 bbl per trip at $1.50/bbl Savings per round trip = $6,000 At 30 trips/yr, savings = $180,000/yr
Total cost per year = $54,675	Total savings per year = $180,000

*Estimated procurement and installation cost based on AiResearch analysis.

TABLE 14

COST SUMMARY - METHOD

Costs	Savings
Installation Costs 3 units (1.5 x Method I) = $77,000/yr Fuel Costs (1.5 x Method I) = $ 550/yr Maintenance Cost = $ 4,000/yr	Reclaimed Oil 100,000 tons of ballast contains approximately 0.4 percent oil or 400 tons per trip, or about $4,500 per round trip x 30 round trips Savings = $135,000/yr Reclaimed Cargo Space Space of slop tanks = 7,000 tons Value per ton per round trip $2.50 Savings per round trip = $2.50 x 700 = $17,500 x 30 trips Savings = $525,000/yr Reduced Repair Costs Based on normal (using Butterworth) repair costs for 200,000-dwt tanker of $3,000,000 over 20 yr ($150,000/yr average) and the fact that corrosion rate can be reduced 15-fold (API data), assume 2/3 reduction in steel replacement Savings = $100,000/yr
Total costs per year = $81,550	Total savings per yr = $760,000

TABLE 15

COST SUMMARY - METHOD III

Costs	Savings
Installation Costs 8 units (4 x Method I) = $205,000 Fuel Costs 8 units for 25 hr per round trip = (30 trips/yr) $5,400 Maintenance Costs = $ 8,000	
Total costs per year = $218,400	Total savings per year = $760,000 (same as Method II)

The discussion above has attempted to give an order of magnitude in the savings realized by using the 2000-gpm centrifugal oil/water separator. Not only is treatment of oily ballast water a legal requirement, it is also economically attractive. The basic improvement of the centrifuge unit proposed herein over static settling type coalescers is that the unit occupies only one-fortieth the volume required to handle similar rates of throughflow.

Based upon comparison with a settling tank/coalescer type separator of equivalent throughflow (500 ton/hr), the savings in displacement tonnage is 80 tons per unit. This equivalent cargo space would amount to a dollar savings of over $30,000 per unit over a 5-yr period. The design of the unit reduces the power requirements to one-tenth of a conventional centrifuge. In addition, the speed of the unit can be adjusted to handle various kinds of gravity oil emulsions. Therefore, resulting separation performance (water quality) can be varied as necessary to meet harbor or inland requirements. The capability of the centrifuge in providing an efficient, compact, long-life, separation system for a variety of inlet conditions makes it an ideal candidate for any oil tanker requiring treatment of oily ballast water.

Oil Field Waste Water Treatment

The following is an example from a study made by a major oil company on the economics of a centrifuge system in the treatment of waste water in an oil field on the Southern California coast. The requirements involved handling 500,000 bbl/day of skim tank water that averaged approximately 200 mg/l oil, and reducing the oil content to less than 15 mg/l.

1. Conventional Waste Water Treatment with Filtration

Capital:		
$8.8/bbl/day x 500,000 bbl/day		$4,400,000
Future operating expense for 10 years:		
$0.006/bbl/day x 500,000 bbl/day x 365 days/yr x 10 yr =	$11,000,000	
Present worth of future operating expense at 10 percent discount factor:		
0.52 x $11,000,000 =		5,700,000
Approximate present value of total future costs		$10,100,000

2. Centrifuge Waste Water Cleanup System

Capital:		
20,000 bbl/day unit*	$50,000	
Miscellaneous hookup	20,000	
Total	$70,000	
500,000 bbl/day capacity		$ 1,700,000
Future operating expense for 10 years:		
$30/bbl/day x 500,000 bbl/day x 365 days/yr x 10 yr =	$2,700,000	
Present worth of future operating expense at 10 percent discount factor:		$ 1,400,000
Approximate present value of total future costs		$ 3,100,000

3. Savings Using Centrifuge:

Approximate present value of potential savings in total future costs:	$7,000,000

---

*Estimated centrifuge cost based on AiResearch analysis

SECTION X

ACKNOWLEDGMENTS

The design, development, and test supervision of the prototype skimmer/centrifuge was performed by a team from AiResearch Manufacturing Company, a division of The Garrett Corporation, under the direction of Mr. J. S. Tyler, Program Manager. Early system concepts and centrifuge design were completed by Mr. J. W. Abbott. Mr. D. S. Wimpress was responsible for design and development of the skimmer and the at-sea test program. Centrifuge development was supervised by Mr. R. W. Lewis, and Dr. John Fallon made the analyses of the size and distribution of particles throughout the centrifuge.

Mr. J. Malberti, of California Shipbuilding and Dry Dock Company, made the structural design of the skimmer barge.

Mr. C. Lang, Ocean Science and Engineering, assisted in the marine engineering and oceanographic aspects of the project.

The practical knowledge and background experience with oil spills provided by Mr. K. S. Elmes, President, General Marine Transport of Santa Barbara, and by the boat crews, is gratefully acknowledged.

Mr. E. O. Kartinen, Chief Engineer, Technical Services, Signal and Gas Company, provided valuable assistance in the centrifuge design and technical liaison with the oil industry in obtaining test facilities and materials.

The support of the project by the Federal Water Quality Administration (now a part of the Environmental Protection Agency) and the help provided by Mr. Allen Cywin, Director, Division of Applied Science and Technology; Mr. Harold Bernard, Chief, Agriculture and Marine Pollution Control Branch; Mr. R. T. Dewling, Director of Edison Laboratories; and Mr. Gerald Stern, Project Officer, is acknowledged with sincere thanks.

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SECTION XI

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SECTION XII

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SECTION XIII

GLOSSARY AND ABBREVIATIONS

API Gravity - An arbitrary scale used by the petroleum industry in the United States to describe the specific gravity of oils. The relation between degrees API and specific gravity is expressed by the following equation:

$$\text{Degrees API} = \frac{141.5}{\text{sp gr } 60^{0}/60^{0}\text{F}} - 131.5 = {}^{0}\text{ API}$$

Boom - A device of considerable length that will float on the surface of a body of water, and form a fence or dam to restrain the surface movement of oil. Booms are usually flexible to conform to the water surface contours under various sea conditions.

Centrifugation - The process of centrifuging; the process of separating oil and water by subjecting it to centrifugal force with a centrifuge drum.

Emulsion - A mixture of oil and water in which the oil is distributed throughout the water in small droplets.

Flow Splitter - A device at the downstream end of the centrifuge drum to prevent the oil layer from passing into the water discharge.

Hertz - A unit of cycle frequency measurement. One Hertz equals one cycle per second.

Quiet Pond - The central portion of the skimmer barge, bounded by the aft bulkhead, the twin hulls, the spillway and the louvered bottom.

Skimmer, Skimmer Barge - The sea-going vessel that supported the centrifuge and other equipment involved in the recovery of oil slicks. The vessel was specially designed and constructed to skim the surface of a body of water.

Specific Gravity - The ratio of the density of a substance to the density of pure water at 4^{0}C.

Spillway - The underwater structure that extends across the entrance to the skimmer barge. The spillway limits the amount of water that enters the quiet pond.

Wave Fence - A device that contains a series of spaced vertical elements, and extends across the quiet pond to reduce the wave action.

Wave Gate - A horizontally-hinged door at the entrance to the skimmer quiet pond.

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°API - Degrees API (See API Gravity)

bbl - Barrel or barrels (a unit of measurement equal to 42 U.S. gallons)

F - Fahrenheit

gm - Gram

gm/l - Grams per liter

GPM - Gallons per minute

mg/l - Milligrams per liter

ml - Milliliter

mm - Millimeter

RPM - Revolutions per minute

SECTION XIV

APPENDIXES

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APPENDIX I

INSTRUMENTATION

The skimmer barge was instrumented to provide data as to the environmental conditions and performance of the various equipment. A summary of this instrumentation is given in Table 16.

PROCESSED FLUIDS FLOW MEASUREMENT

Weir pump flow rate, overflow rate, and centrifuge inlet flow were measured by timing the rise (or fall) of the surface level in the surge tank when selected valves were opened or closed. The centrifuge oil flow rate was measured by three different methods at various times during the tests.

(a) Time to fill a quart jar

(b) Time to fill oil receiver between two marks placed 1/2-barrel (21 gal) apart

(c) Positive displacement flowmeter

The oil flow rate from the surge tank oil overflow was measured either by (1) measuring barrels of oil pumped from the oil transfer barrel and then subtracting the centrifuge oil flow rate or (2) measuring 1/2-barrels drawn off the oil overflow weir.

WAVE HEIGHT MEASUREMENT

The ocean wave heights were measured by means of a spar buoy as shown in Figure 93. The buoy consists of a calibrated 24-ft pole that floats vertically in the water. A 14-in.-diameter saucer at the lower end, which is nominally some 16 ft underwater, damps vertical motion of the pole. A small flotation ring located 8 ft above the saucer brings the center of flotation above the center of gravity so that the pole remains upright. As waves pass the pole, there is very little change in buoyancy because of the small cross section of the pole. Therefore, the pole stands still in the water as the surface waves pass by. Wave height and frequency are determined visually by observing the rise and fall of the water surface on the calibrated portion of the pole.

WIND MEASUREMENT

Wind velocity was determined by means of a Danforth Model M50SB wind velocity indicator. The 3-cup generator was mounted approximately 10 ft above the deck of the barge. Two scales were available through a selector switch: 0 to 25 knots and 0 to 125 knots.

Wind direction was obtained with a Newport Supply Company Model N198 Windetector wind vane located adjacent to the anemometer generator.

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TABLE 16

SEA DRAGON INSTRUMENTATION

	Variable	Instrument	Range	Least Count	Source
Sea	Wave height	Spar buoy	±6.0 ft	1 ft	Special build
	Wave frequency	Stopwatch		0.2 sec	
	Wave direction	Compass	0 to 360 deg	5 deg	Airguide Model 87
	Type	Visual	--	--	
	Water temperature	Thermometer	0 to 120°F	1°F	
Air	Velocity	Anemometer	0 to 25, 0 to 125 knots	1, 5 knots	Danforth Model MSB
	Direction	Wind vane	No scale	Visual	Windetector
	Temperature	Thermometer	0 to 120°F		
Barge	Draft	Draft lines	0 to 6 ft	3 in.	Painted
	Velocity	Sailboat speedometer	0 to 5, 0 to 10 knots		Kenyon Model KSI
	Pitch magnitude	Inclinometer			
	Pitch period	Stopwatch*	--		
	Roll magnitude	Inclinometer			
	Roll period	Stopwatch*			
	Direction	Compass	0 to 360 deg	5 deg	Airguide Model 87
Quiet pond	Inlet flow	Calculate (draft times speed)	--	--	--
	Wave gate opening	Marks on gate bracket	0 to 36 in.	1 in.	Special build
	Underwater condition	Port holes	Not applicable	--	Special build
	Underwater currents	Ribbons	Not applicable	--	Special build

*Used elsewhere

TABLE 16 (Continued)

	Variable	Instrument	Range	Least Count	Source
Processed fluids	Weir pumps flow rate	See text			
	Centrifuge inlet flow rate				
	Tank overflow flow rate				
	Centrifuge oil flow rate				
	Tank oil flow rate				
	Oil viscosity	Samples collected and sent to laboratory			
	Oil in water				
	Water in oil				
	Oil gravity				
Equipment	Centrifuge speed	Tach on centrifuge			
	Weir pump	Hand-held tachometer	0 to 4000 rpm		Stewart-Warner 757-W
	Ballast tanks	Calibrated rod	0 to 8 ft	1 in.	Special build
	Towing force	Dynometer	0 to 10,000 lb	100 lb	Dillon Type AN
Centrifuge	Speed and chronometer	Tachometer	0 to 3500 rpm	--	Part of centrifuge
	Pump inlet pressure	Gauge	0 to 50 psi		Part of centrifuge
	Pump discharge pressure	Gauge	0 to 100 psi		Part of centrifuge
	Oil discharge pressure	Gauge	0 to 50 psi		Part of centrifuge
	Diesel cooling water temp	Gauge	0 to 200°F		Part of centrifuge
	Diesel oil pressure	Gauge	0 to 80 psi		Part of centrifuge
	Diesel torque converter pressure	Gauge	0 to 300 psi		Part of centrifuge
	Diesel fuel inlet pressure	Vacuum gauge	0 to 30 in. Hg		Part of centrifuge
	Oil mist manifold pressure	Gauge	0 to 100 in. H_2O		Part of centrifuge
	Bearing temperature	Battery powered bridge	0 to 50 mv		Lab supply

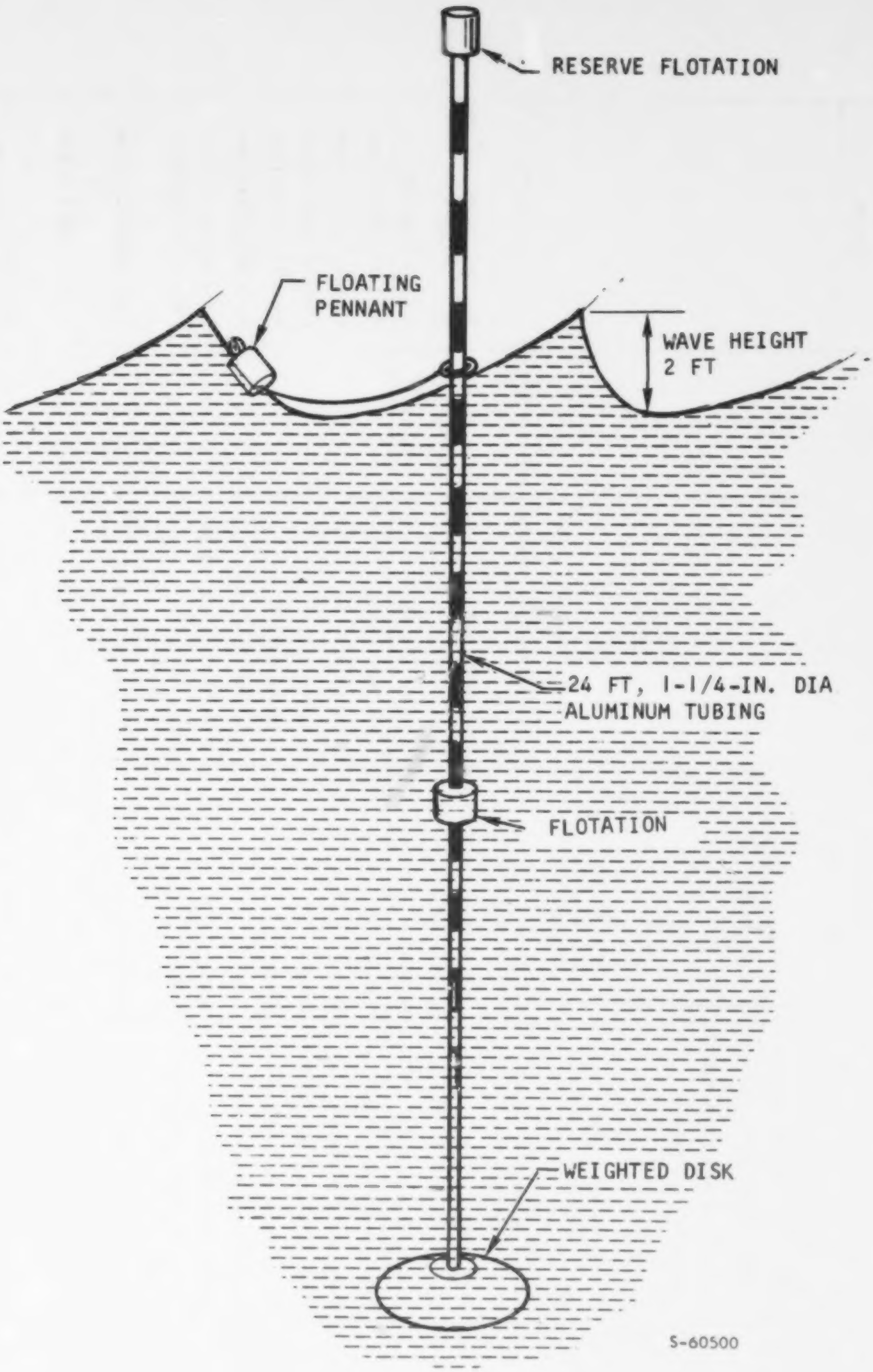

Figure 93. Wave Height Measuring Device

SKIMMER SPEED

A Kenyon Model KSI sailboat speedometer, with selectable ranges of 0 to 5 knots and 0 to 10 knots, was installed to obtain skimmer speed. This equipment, however, was subject to malfunctions and speeds were usually determined by throwing small floating objects onto the water and timing their passage the length of the barge.

WATER TEMPERATURE

A dial thermometer was installed in the surge tank to indicate the temperature of the water being processed, which was the same as the seawater temperature.

TOWING FORCES

Towing forces were measured with a Dillon Model AN 0 to 10,000 lb (±2 percent) dynamometer. When higher than 10,000-lb peak loads were expected, the dynamometer was installed as is shown in Figure 76. Towing forces varied considerably as the towboat and skimmer passed over the ocean swells. The maximum towing force was indicated by a needle follower; the minimum and average were determined by observation.

APPENDIX 2

OIL/WATER TEST, SAMPLE ANALYSIS METHOD

METHOD USED FOR DETERMINING CONCENTRATION OF OIL IN WATER

The trichloroethylene method was used in determining the amount of oil in the water during the centrifuge and sea skimmer test. This method was used rather than the Soxhlet extraction method as discussed in the FWQA manual entitled "FWPCA Methods for Chemical Analysis of Water and Wastes," dated November 1969. The following comments are given to justify the method used.

(a) The asphaltene content of the oils tested varied from 4 to 10 percent. Asphaltenes are soluble in trichloroethylene; however, this material is only slightly soluble in hexane. This would reduce the accuracy of the hexane method.

(b) The oils used contained varying amounts of volatile hydrocarbons that would be lost in the hexane method as outlined in page 205 of the FWQA manual.

(c) Calibration factors were determined for each oil used in the program. This resulted in an accuracy of ±10 percent for the colorimetric method. Data for verification of the hexane Soxhlet extraction method accuracy are not available per page 209 of the FWQA manual.

(d) The large number of samples obtained during the test program required rapid method of determining oil content. The colorimetric requires about 10 min/sample; the hexane method takes 6 to 8 hr.

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SIGNAL OIL AND GAS COMPANY

Technical Service Laboratory
Long Beach, California

Colorimetric Determination Of Oil In Waste Waters

Introduction

The following colorimetric procedure was devised for rapid determinations of small amounts of oil in waste waters. Both emulsified and floatable oils are measured. The oil is extracted from the water by intimate contact with an organic solvent. Although any good colorless organic solvent may be used, trichloroethylene was selected because it has a slightly higher boiling point (87°C) than similar chlorinated solvents. Since it has a solubility in water of less than 0.1 percent and a specific gravity of 1.466 at 20°C, a good separation of the two liquids is obtained.

Apparatus

Balance

Colorimeter

Cuvettes

1000 ml separatory funnel with no-lubrication stopcock or with all lubricant removed from ground glass surfaces

100 ml graduate

500 ml graduate

Glass funnel

Pint-sized sample bottle with caps

Weighing flask

China marking pencil

Ringstand

Aluminum foil

Reagents

Trichloroethylene

Procedure

1. Sampling Procedure. Obtaining a representative sample is of the utmost importance. It is at this point where the greatest error may be introduced in any residual oil determination. Since every waste water sampling has its own peculiar difficulties, no definite procedure can be given which would be applicable in all cases. In general, samples from open discharge lines should be taken in wide mouth pint bottles, preferably, the Mason type. Samples from lines with sample cocks may be obtained in any suitable pint-size container. During sampling the bottle should not be overflowed. Before turning on the cap, place a square of aluminum foil over the jar mouth.

2. Laboratory Procedure. Mark the water level on the outside of the sample jar with a china marking pencil. Remove the cap with the foil and using a funnel pour the contents of the jar into the separatory funnel. Measure a volume of 100 ml trichloroethylene in a 100 ml graduate. Transfer approximately 50 ml of this volume into the sample jar, recap, and shake vigorously. Remove the cap and pour the solvent into the separatory funnel. Repeat using approximately 25 ml of the remaining solvent to rinse off oil adhering to walls of the bottle. Before removing the funnel, rinse it with the remainder of the solvent.

   Stopper the separatory funnel and shake. Set aside for a few minutes to allow water and solvent separation. During this time fill the sample jar to the water level mark with tap water. Transfer this water into the 500 ml graduate and record its volume. When the solvent in the separatory funnel has settled out, open the stopcock and obtain a sample in the colorimeter cuvette. Occasionally it may be necessary to filter the solvent containing the extracted oil to remove small suspended water droplets. If this is necessary, moisten the filter paper with a clean solvent before filtering. This will aid in retaining the water and allowing the solvent phase only to pass through the filter paper.

   Zero the colorimeter with a solvent blank and read the sample at 400-465 m μ.

   Calculate as follows:

   $$\text{Oil (mg/l)} = \frac{\text{Colorimeter Reading}}{\text{Sample Volume}} \times \text{solvent volume} \times \text{calibration factor.}$$

3. Standardization. Since crude oils exhibit a great range in chemical and physical properties, it is impossible to measure minute quantities of oil with a great degree of accuracy and reproducibility in oil field waste waters by any method. To reduce errors caused by these variables, it is suggested that calibration factors or curves be determined for each field from which samples for oil determinations might be encountered.

Samples of representative crude are weighed to the nearest mg. If the volatility of the crude is high enough to cause weight changes when using an open container, it is suggested that a Lunge-type weighing flask be used. For most crudes, a watch glass is satisfactory. Samples of 50 mg or less are preferred for standardization. The addition of 100 mls. of solvent to 50 mg of oil gives a concentration of 500 gm/l. Aliquots of this stock solution are then diluted with solvent to obtain lower concentrations. Depending upon the type of colorimeter used, the standard containing 500 gm/l will probably exceed the upper limit of the colorimeter scale. With the Klett-Summersen colorimeter, it was noted that above 250 gm/l the calibration factors became increasingly larger compared to those obtained at lower concentrations.

Readings taken at various concentrations are recorded and the factor is determined as follows:

$$\text{Calibration Factor} = \frac{\text{gm/l oil in standard}}{\text{Colorimeter reading}}$$

Usually there is a variation of less than 5 percent between calibration factors, so an average calibration factor is used.

Limitations of Test

This method was devised in an attempt to obtain a rapid colorimetric procedure for determining oil in waste water. As such, the results may be affected by any of the limitations and errors inherent in colorimetric determinations.

In practice, the accuracy and reproducibility of results compares favorably with those obtained by the use of time-consuming flocculation and extraction methods.

APPENDIX 3

CENTRIFUGE TEST DATA

Presented in this section are data that describe the performance of the centrifuge.

Data in Group 1 were taken during one of the first runs on the centrifuge wherein the general characteristics (pressures, flow rates, and bearing temperatures) were being investigated.

Data in Group 2 were taken the following day and include further investigations into the oil separation characteristics.

Data in Group 3 were taken at essentially constant centrifuge speed but with the flow rate varied by means of the throttling valve downstream of the pump. The oil in and out, and the water flow rates, were measured with flowmeters. From this was obtained the flow emulsion percentage (last column). The lab emulsion percentage was obtained by analysis of samples taken of the inlet emulsion. The samples columns show the mg/l of oil in the discharge water and the percent water in the discharge oil.

Data in Group 4 were taken at a slightly lower centrifuge speed.

Group 5 includes data taken at a number of different conditions to provide a broader background for the analysis of the preceding data. To determine some of the mechanical problems, some miscellaneous tests were also made, such as the backflow oil test to test the seals.

These above-described data were all taken on the original model of the centrifuge, which was then modified and the following data were taken.

Group 6 data are summaries excerpted from raw data sheets similar to sheets 1 through 5, to arrange the data with certain parameters constant.

Group 7 data were taken to obtain the fuel consumption rates for the centrifuge under several operating conditions.

Form 796

Time	Speed, rpm			Pressures, psig				Flow Rates, gpm			Brg Temp., °F		Samples, ppm
	Chron	Engine	Cent.	Pump IN	Pump Out	Oil Out	Water Out	Water In	Oil In	Oil Out	Inlet	Outlet	
1315	1.24	Start									68,68	73	WEIR PRESSURE DROP TESTS
1326	1.30		1000			1.		108	0	0			
1334	1.35		1000		20	2.		168	0	0	73,73	73	
1338	1.38		1000		20	2.8		217	0	0			
1340	1.39		~1000		20	50.		280	0	0			The 50 psi Oil Outlet Pressure Builds Slow Bleeds Fast
1345	1.43		~1000		20	27		375	0	3	75,75	75	Oil Out Pressure Taken 30 sec After Closing Its Valve
1350	1.46		~1000		20	37		435	0	0			Oil Out Pressure Taken 30 sec After Closing Its Valve
1355	1.48		~1000		19	48		364	0	0			Oil Out Pressure Taken 30 sec After Closing Its Valve
1358	1.51		~1000		20	47		297	0	0			Oil Out Pressure Taken 30 sec After Closing Its Valve
1403	1.55		1100		20	35		253	0	0	76,76	76	Oil Out Pressure Taken 30 sec After Closing Its Valve
1408	1.58		1100		20	2.8		130	0	0			Oil Out Pressure Taken 30 Sec After Closing Its Valve
1419										*			*33.5 Gallons of Oil Inserted Into Centrifuge;
													Water Flow Rate Reduced to < 100 gpm
1420	1.66		1050			6.6		<100	0	0			
1421	1.69		1525			10.5		<100	0	0	76,76	76	
1426	1.73		2075			22.		<100	0	0	74,74	74	
1430	1.78		2500			31.		<100	0	0	78,78	78	
1433	1.84		3125			41.		<100	0	0	76,76	76	
1435	1.90		3650			57.		<100	0	0	84,84	84	
1440	1.94		3400										Engine Temperature >195; Drop Speed; Increase Cooling
													Water into Engine, Strainer Must be getting dirty
1440+	1.96		3470			46		<100	0	0	81,81	81	
1442	2.00		3325			45		<100	0	0	81,81	81	
1450	2.12		3150		80	2		417	5	6.6			
1451	2.17		3150		80			425	3.3	6.6	81,81	81	
1458	2.31		3500		95			425			85,85	85	
1500	2.37		>3500					525	2.5	3.3	86,86	86	Oil in Water Effluent (Fair Separation)
1507		Decrease											
1515		Stop											
2 hr 1516													
													Inlet Seal Leaking Badly After Water Inlet Fluid
1625		Started											Reduction
1635	2.76		3575					525	16.8	16.8	80,83	83	
1640		Stop											

ALTITUDE EQUIPMENT DIVISION		
CALCULATED		
RECORDED	R.W.I.	5/12/7
DRAWN		
CHECKED		
APPROVED		

CENTRIFUGE PERFORMANCE DATA

Original Data in Notebook

AIRESEARCH MANUFACTURING CO.
LOS ANGELES CALIFORNIA

Group 1

1 of 2

Form 796

Time	Speed, rpm Chron	Engine	Cent.	Pressures, psig Pump In	Pump Out	Oil Out	Water Out	Flow Rates, gpm Water In	Oil In	Oil Out	Brg. Temp., °F Inlet	Outlet	Samples, ppm
													The Centrifugal Pump was Disconnected from the Diesel and
													the Following Data was Taken
1740		Start											
1750	2.97		2300					325	5.25		78,78	78	
1755			3300					295	4.20	1.5	78,78	78	Low Oil Concentration in Water Sample. This was the Best
													Separation of the Day (Good Separation)
1800		Stop											

ALTITUDE EQUIPMENT DIVISION		
CALCULATED		
RECORDED	R.W.L.	3/12/7[illegible]
DRAWN		
CHECKED		
APPROVED		

CENTRIFUGE PERFORMANCE DATA

Original Data In Notebook

AIRESEA[illegible] MANUFACTURING CO.
[illegible] ANGELES CALIFORNIA

Group 1

2 of 2

Form 796

NOTES	TIME	RPM'S CHRON	ENGINE	CENT.	PRESSURES ~ PSIG PUMP IN	PUMP OUT	OIL OUT	WATER OUT	FLOW RATES ~ GPM WATER IN	OIL IN	OIL OUT	BRG TEMP °F INLET	OUTLET	SAMPLES ~ PPM WATER			OIL IN	[illegible]		
	1430	3.18	START									75 75	75							
	1440	3.30	1750	2650	0	45	4	0				77 80	80	✓						
	1455	3.55	2000	3340	"	53	0	"	325	1.34	"	87 95	89	✓						
	1504	3.74	"	3300	"	55	0	"	"	2.8	4.0	89 94	89	✓			BLEED	.41		
	1510	3.85	"	3325	"	65	2	"	"	5.0	6.5	89 94	89	✓			PUMP	.85		
	1515	3.94	"	3300	"	55	1	"	327	5.0	6.5	91 94	89	✓			PUMP	1.52		
	1522	4.07	"	3300	"	55	2	"	"	10.8	12.6	92 99	92	✓			BLEED	1.51		
	1528	4.17	"	3250	"	63	7	"	"	10.7	13.0	92 99	92	✓			BLEED	3.06		
	1535	4.32	"	3275	"	70	10	"	"	22.0	15.7	94 99	94	✓			PUMP	8.17		
	1543	4.43	"	3220	"	70	5	"	425	11.5	15.0	92 99	91	✓			PUMP	6.3		
	1550	4.57	"	3230	"	80	10	"	420	12.3	16.2	95 100	96	✓			BLEED	2.64		
①	1552	4.63	"	3350	"	80	9	"	193	12.0	13.0	98 100	98	✓			PUMP	2.84		
	1600	4.78	"	3350	"	60	9	"	188	4.1	10.7	98 100	98	✓			PUMP	5.9		
	1610	4.95	"	3350	"	60	5	"	196	4.8	6.1	97 99	98	✓			PUMP	2.14		
	1618	5.08	1600	2600	"	35	2	"	150	4.3	11.5	94 94	94	✓			BLEED	2.31		
	1621	5.14	"	2580	"	30	0	"	150	4.4	5.4	91 91	91	✓			BLEED	2.80		
	1625		STOP														PUMP	2.86		
	1655		START									85 85	85							
②	1715	5.43	2000	3330	0	80	0	0	100	5	0	86 85	86							
	1735	5.83	"	3330	"	90	0	"	145	4.3	3.1	86 86	86	✓			PUMP	—		
	1743	5.95	"	3330	"	90	1	"	135	4.8	5.8	88 88	88	✓			BLEED	2.88		
	1745		STOP														PUMP	3.00		
③	1800			STOP																

③ CENTRIFUGE SPEED COUNTER WAS PICKING UP A STRAY SIGNAL OF 120 Hz OR LESS UNTIL 1705 HRS THEREFORE SPEED MAY BE SLIGHTLY [illegible]

② WATER INSERTED INSTEAD OF OIL THUS INVALIDATING THE 1715 DATA

① WATER LOOKED VERY CLEAN WHEN SAMPLE WAS TAKEN, HOWEVER, MOMENTS LATER IT TURNED BLACK WHEN THE OIL OVERFLOWED THE WEIR.

ALTITUDE EQUIPMENT DIVISION		
CALCULATED		
RECORDED	3/18/70	R.W.L.
DRAWN		
CHECKED		
APPROVED		

CENTRIFUGE PERFORMANCE DATA

Group 2

AIRESEARCH MANUFACTURING CO.
LOS ANGELES CALIFORNIA

1 of 1

		SPEED ~ RPM			PRESSURES ~ PSIG				FLOW RATES ~ GPM			BRG TEMP °F		SAMPLES ~ PPM			LAB	FLOW
NOTES	TIME	CHRON	ENGINE	CENT	PUMP IN	PUMP OUT	OIL OUT	WATER OUT	WATER IN	OIL IN	OIL OUT	INLET	OUTLET	WATER	WATER	OIL %	[illegible] %	[illegible] %
	1110	5.98	START													= H_2O		
	1116			START								65 65	65					
	1130	6.17	1850	3000					100									
	1140	6.33	2000	3325	0	80	0	0	200	1	.87	87 92	92	105 105	105	30	.29	.5
	1151	6.74	2000	3300	0	90	0	0	298	1.6	1.6	74 94	88	180 180	160	31	.31	.54
	1206	700	2000	3275	0	90	0	0	398	2.0	3.2			290 290	290	26	.58	.50
	1222	728	2000	3275	0	95	0	0	497	2.5	2.87	95 95	95	290 290	290	34	.33	.5
	1225	7.35	STOP															
	1325	7.35	START									80 82	81					
	1357	7.57	2050	3350	0	90	0	0	204	3.0	4.0	77 87	87	235 235	235	25	1.00	1.45
	1411	7.84	2050	3350	0	90	2	0	295 [illegible]	4.5	5.6			410 410	390	26	.87	1.5
	1425	8.08	2050	3280	0	90	3	0	394 [illegible]	6.6	8.4	91 95	95	580 580	580	24	1.07	1.65
	1440	8.37	2050	3360	0	90	4	0	194 [illegible]	6.15	8.7	90 96	96	270 270	270	34	1.45	3.06
1	1453	8.64	2050	3250	0	90	3	0	493 [illegible]	6.8	8.2	92 97	97	600 600	600	24	.87	1.36
	1506	8.90	2100	3370	0	90	3	0	493 [illegible]	7.5	9.0	92 96	96	600 600	580	30	1.02	1.5
	1521	9.19	2130	3425	0	95	5	0	291 [illegible]	9.0	12.3	92 96	96	450 450	450	28	1.20	3.0
2	1531	9.46	2130	3425	0	95	~13	0	188 [illegible]	12.0	13.5	85 97	97					6.0
	1535		STOP															

② JUST PRIOR TO SAMPLING 1531.5 THE WATER WENT BLACK; ACCUMULATION PERIOD IS MIN.

① EXTRA POINT

OIL GRAVITY 21.5 ON FIRST SAMPLE 1140 HRS.

ALTITUDE EQUIPMENT DIVISION		
CALCULATED		
RECORDED	3/17/70	R.W.L.
DRAWN		
CHECKED		
APPROVED		

CENTRIFUGE PERFORMANCE DATA

TEST DATE 3/17/70

Group 3

AIRESEARCH MANUFACTURING CO.
LOS ANGELES CALIFORNIA

1 of 1

			SPEED ~ RPM		PRESSURES ~ PSIG				FLOW RATES ~ GPM			°F TEMPS		SAMPLES ~ PPM		LAB SAMPLES		EMUL	CONC IN	
NOTES	TIME	CHRON	ENGINE	CENT.	PUMP IN	PUMP OUT	OIL OUT	WATER OUT	WATER IN	OIL IN	OIL OUT	OUTLET	INLET	WATER	WATER	OIL OUT	EMUL %	EMUL %	BEST OIL	
	1035	9.50	START									74	74 74			H_2O %	OIL %			
	1104	9.88	1750	2780	0	65	0	0	199	1.08	1.88	82	82 79	115 105	110	2.3	.55	.54	27	
	1110	9.97	1800	2780	0	75	0	0	298	1.37	1.92	87	87 82	200 285	200	4.0	.48	.46	36	
	1133	10.34	1800	2775	0	70	0	0	398	2.03	2.82	88	88 85	290 285	290	3.8	.57	.51	42	
1	1140	10.43	1750	2750	0	70	0	0	497	2.50	2.75	92	91 87	270 280	260	2.8	.39	.50	48	
1	1148	10.59	1800	2850	0	80	0	0	197	2.95	2.50	89	89 83	208 165	165	2.5	1.13	1.48	29	
1	1153	10.76	1750	2810	0	70	1	0	295	4.35	2.84	91	91 85	85 88	90	4.2	.51	1.45	36	
	1205	10.83	STOP																	
2	1330		START									77	77 77							
3	1350	11.09	1750	2770	0	75	0	0	398	0	TRIC	86	86 86						42 48	
4	1405	11.32	1750	2750	0	75	0	0	395	5	2.6	87	88 89	240 220	125	4.8	.50	.6		
5	1414	11.44	1750	2750	3	80		0	395	14.	9.3	87	87 87							
6	1420	11.54	STOP																	

6 WATER FLOW METER FAILED; TURBINE CAME OFF ITS SHAFT.
5 HEAVY OIL CARRY OVER BEFORE INLET WATER COULD BE ADJUSTED
4 Repeats Run of 1180
3 BY CLOSING VALVE BETWEEN GAGE & CENT. THE PRESSURE READS THE HIGHER CENT. INLET PRESSURE.
2 INLET OIL TAKEN FROM OIL SUMP SURFACE; CUT ≈ 60% AND ALL OIL INLET FLOWS HAVE BEEN ADJUSTED FOR H_2O CONTENT; [illegible]
1 INLET OIL MAY BE CUT WITH UNKNOWN AMOUNT OF WATER

OIL GRAVITY ON 1104 SAMPLE 21.5 API.

ALTITUDE COMPONENT DIVISION		
CALCULATED		
RECORDED	3-18-70	RWL
DRAWN		
CHECKED		
APPROVED		

CENTRIFUGE PERFORMANCE DATA

TEST DATE 3-18-70

AIRESEARCH MANUFACTURING CO.
LOS ANGELES CALIFORNIA

Group 4

			SPEED ~ RPM		PRESSURES ~ PSIG				FLOW RATES ~ GPM			BRG TEMPS °F		[illegible] ~ PPM		[illegible] ~ %		FLOW %		
NOTES	TIME	CHRON	ENGINE	CENT	PUMP IN	PUMP OUT	CENT. IN	OIL OUT	WATER IN	OIL IN	OIL OUT	OUTLET	INLET	WATER	WATER	OIL OUT	[illegible] IN	[illegible] IN		
	1055	1157	START									70	70 70							
1	1101	1158		START																
2	1114	11.68	800	1130	15	15	13	7	460	0		72	72 72							WTR PRESSURE DROP TEST
2	1122	11.74	800	1050	15	15	13	7	440	0										
2	1129	11.79	800	1060	5	15	12	5.8	372	0		74	74 74							
2	1132	11.81	STOP																	
2	1142			STOP	30	5	2.5	3.0	400											
2	1149			"	24	<5	~1	2.0	334											
2	1154			"	10	<5	~0	0.9	235											
	1252		START									76	76 76							
	1257	11.84		START						0										BACK PRESS. TEST w. VOL. INTRODUCE
	1340	12.41	1750	2750	0	20	42	0	400	2.0				165	200 165				PUMP	
	1347	12.56	1750	2750	0	70	42	25	400	1.98		80	75 75	140	140 130				PUMP	
	1400	12.76	1750	2250	0	70	42	25	400	2.05	3.0			105	120 105				BLEED	
3	1406	12.88	1750	2250	0	70	42	0	400	2.0	3.15			140	125 130				BLEED	
4	1410	12.92	STOP																	
	3/26/70		BACK FLOW OIL TEST																	
	0925	12.93	START																	
	1010	13.26	IDLE	START	0	0	0	0	~100	0	0	70	70 70	0	0					
	1020	13.39	1750	2700	0	70		12.5	400	0	0									
5	1036				0	70		33	400		0	80	72 72	0						
6	1038	13.67	1750	2700	0	20		42	400	3.3				1.3						
	1045	13.81	1750	2700	0	70		44	400	9gal/hr				40						
	1046		STOP																	
	1101																			
	1125	13.83	START	START					400					146						
7.	1129	13.97	1700	2650	0	60	42.5	13	400	1.35		72	72 72							
	1140	1407	STOP																	

7 OIL FLOWING OVER WEIR GAVE MAXIMUM OIL DISCHARGE PRESSURE OF 45 PSIG. COULD NOT CLEAN UP WATER BY [illegible]

6 APROX. 2 GALLONS OIL IN CENTRIFUGE

5 OIL AT LIP SEAL

4 SHUT DOWN; SUMP FULL.

3 THERMOCOUPLE READOUT SPARKING

2 OIL OUT PRESSURE UNDER STATIC CONDITIONS

1 INLET FACE SEAL [illegible] LEAKING BADLY BUT STOPPED SHORTLY AFTER IT [illegible]

KIMMON WATER FLOW METER USED

TOTAL RUN TIME TO DATE = 23.45 HRS

ALTITUDE COMPONENT DIVISION
CALCULATED
RECORDED 3/26/70 R.ALL
DRAWN
CHECKED
APPROVED

AIRESEARCH MANUFACTURING CO.
LOS ANGELES CALIFORNIA

Group 5

OIL CONC.		FLOW	PRESS.					
INLET	OUTLET	INLET	INLET	NOTE	I/O			
PPM	PPM	GPM	PSIG					
54	13	194	35	A	4.1			
42	19	340	36	↑	4.2			
62	15	325	35		4.1			
109	61	145	26		1.8			
33	13; 23	105	13	↓	1.8			
27	7	120	23	A	3.9			
62	27	197	68	B	2.3			
59	22	197	68	↑	2.7			
46	23	110	42		2.0			
27	3	157	37		9.0			
66	18; 11	205	50		4.6			
54	12	327	75		4.5			
64	13	315	76		4.9			
23,000	57	165	62		403.			
4,000	59	253	71		68.			
63	11	200			5.7			
39	7; 7	145	49	↓	5.6			
133	12	197	55	B	11.1			
92	14	315	97	C	6.6			
43	6	257	84	↑	7.2			
41	8	145	61		5.1			
39	10	95	48		3.9			
44	12	140	62		3.7			
41	2	95	35		20.5			
37	2	120	48		18.5			
107	18	240	83		5.9	A =	1750 ±	150 RPM
166	14	265	86	↓	11.9	B =	2750	" "
140	12	193	74	C	11.7	C =	3300	" "

CALCULATED		
RECORDED	R.W.L.	7/2/70
DRAWN		
CHECKED		
APPROVED		

DATA SUMMARY
OIL WATER SEPARATOR
140°F SKIM TANK WATER

AIRESEARCH MANUFACTURING CO.
LOS ANGELES, CALIFORNIA

Group 6

Rev. 7/2/70

Pg 1 of 5

OIL CONC.		FLOW	PRESS.		
INLET	OUTLET	INLET	INLET	NOTE	I/O
40,000	71	107	25		564
18,000	~500	275			36
16,000	51	190	38	D	314
42,000	188	100	32		223

D. DATA FROM 5/26/70 ON "MIXED OIL" 25 TO 31 API

CALCULATED		
RECORDED		
DRAWN		
CHECKED		
APPROVED		

Data Summary - Oil Water Separator
at 1750 ± 150 RPM

Group 6

AiRESEARCH MANUFACTURING CO.
LOS ANGELES, CALIFORNIA

Rev 7/2/70

Pg 2 of 5

OIL CONC.		FLOW	PRESS.					
INLET	OUTLET	INLET	INLET	NOTE	I/O			
PPM	PPM	GPM	PSIG					
30,000	248	227	60		121			
23,000	80	200	65	D	288			
11,000	71	200	67		155			
40,000	152	205	69		263			
30,000	142	203	69		211			
17,000	108	188	69		158			
7,000	78	186	68		90			
8,000	71	185	69		113			
11,000	42	187	69	D	262			
4,000	91	200	51		44			
11,000	342	300	69		32			
10,000	400	400	85		25			
11,000	622	475	94		18			
2,000	149	475	93		13			
6,000	216	206	60		28			
20,000	337;352	300	78		58			
2,000	171	400	85		12			
11,000	179	193	64		61			
3,600	300	215	65		12			
520	40	100	50		13			
2,950	31	115	52		95			
32,000	99	110	58		323			
19,600	238	200	68		82			
27,000	254	190	72		106			
18,500	451	290	88		41			
3,200	253	197	64		13			
4,950	200	197	66		25			
16,000	303	197	70		53			
3,700	246	210	64	1	15			
5,900	162	197	65	1	36			
16,900	240	190	65	1	71			
14,300	195;211	195	69		71			
14,300	226	197	68		63			

1. FRESCH [illegible] WATER

CALCULATED		
RECORDED	R.W.L	7/1
DRAWN		
CHECKED		
APPROVED		

Data Summary - Oil Water Separator
at 2750 ± 150 RPM 21 to 26 API -
Amb Sea Water

AIRESEARCH MANUFACTURING CO.
LOS ANGELES, CALIFORNIA

Group 6

Rev 7/2/70

Pg 3 of 5

OIL CONC. INLET PPM	OUTLET PPM	FLOW INLET GPM	PRESS INLET PSIG	NOTE	I/O
2,909	156	197	68		1.9
28	190	197	70	?	
28,108	248	197	72		113
40,000	260	197	74		154
41,025	176	195	74	2	233
111	158	197	71	? 2	
4,200	234	200	68		18
4,300	166	188	70		26
3,800	123	197	71	2	31
4,300	137	197	70	2	31
19,700	68	92	59	2	290
2,947	28	97	52	2	105
3,200	50	96	54		64
15,179	78	92	54		195
5,189	133	190	70	3	39
16,422	361	200	73	3	45
164	253	200	73	?	
6,400	192; 141	190	65		39
29,268	195	185	67		150
5,678	67	190	67		85
346	11	412	90	4	31
78	15; 8	412		4	6.5

4. PUMP MOUNTED ONTO DIESEL

3. 2nd TYPE EMULSION BREAKER

2. WITH TRETONITE 9045 EMULSION BREAKER @ 1qt/HR.

CALCULATED			Data Summary - Oil Water Separator at 2750 ± 150 RPM 21 to 26 API - AHB Sea Water	Group 6
RECORDED	K.W.L	7/1		
DRAWN				
CHECKED			AIRESEARCH MANUFACTURING CO. LOS ANGELES, CALIFORNIA	Rev 7/2/70
APPROVED				Pg 4 of 5

OIL CONC. INLET PPM	OIL CONC. OUTLET PPM	FLOW INLET GPM	PRESS. INLET PSIG	I/O	NOTE
13,000	133; 145	195	84	94.	
9,000	289	296	100	31.	
11,000	311	340	107	35.	
22,000	136	195	92	162.	
19,000	232	300	105	82.	
23,000	145, 156	198	90	153.	
34,000	222	293	106	153.	
48,000	184	193	92	260.	
43,000	207	280	107	161.	
37	13	105	58	2.8	5
52	25	207	89	2.1	↑
37	19	280	88	1.9	↓
40	6	105	58	6.7	5

5. EFFLUENT FROM VACUUM TRUCK

CALCULATED		
RECORDED	R.W.L.	7/1/70
DRAWN		
CHECKED		
APPROVED		

DATA SUMMARY
OIL WATER SEPARATOR
3350 ± 150 RPM ; 21-26 API

Group 6

AIRESEARCH MANUFACTURING CO.
LOS ANGELES, CALIFORNIA

Rev. 7/2/70

Pg 5 of 5

AIRESEARCH MFG. CO.

DATE 7/13/70
PREPARED BY R.W. Lewis
CHECKED BY

CALC. NO.
MODEL
PART NO.

Fuel Consumption & Maximum Flow Test

Diesel Speed RPM	Pump Press.[1] PSIG	Fuel Consumption Time Intervals MIN: Sec 50cc	100cc	150cc	200cc	250cc	300cc	350cc	400cc	NOTE
800	20		1:15	2:02	:	5:10	4:27	7:50	9:08	
1000	30		1:39	2:26	3:15	4:05	4:55	5:44	6:30	
1400	48	0:12.5	0:27	0:46.5	1:09	1:34	1:56	2:23.5	2:48.8	
1400	50	0:15	0:32.5	0:55	1:18.5	1:43.5	2:08.5	2:33.5	2:58.8	
1700	70	0:07.5	0:15.5	0:24.5	0:34.5	0:46	0:58.5	1:12	1:26.5	
1700	70	0:18.5	0:35	0:51.5	1:07	1:23	1:39	1:54	2:09.5	
1700	75	0:12.5	0:25	0:39.5	0:54	1:10	1:25	1:41	[illegible]6.5	2
2000	98	0:06	0:11.5	0:18	0:24	0:31	0:39	0:47	[illegible]5.1	3
2000	98	0:11	0:21	0:31	0:42	0:53	1:03.5	1:14	1:25	4
1400										5

5. "Low flow Water quality test: At full flow the discharge sample contained aprox 100-200ppm oil with 1-2% inlet. At low flow (~30gpm) there was less than 20ppm in the discharge water with 1-3% oil in the inlet.
4. Oil flow rate (regulated cut) 2.2, 2.2, 2.4 sec/qt = 6.8, 6.8, 6.25 gpm.
3. Water flow rate @ 42 + 42.8 sec/ft drop in tank = 300 & 244 gpm
2. WATER FLOW RATE @ 50sec/ft Drop in tank=250gpm; Oil flow rate = 2.5 + 1.8 gallons/min.
1. GAGE ZERO SHIFT +10 PSI; SUBTRACT 10 PSI FROM RECORDED PRESSURES.

Group 7
PAGE 1? OF

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